Incorporating Pavement Sustainability Into Municipal Best Practices

by

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A thesis
presented to the University of Waterloo
in fulfilment of the
thesis requirement for the degree of
Master of Applied Science
in
Civil Engineering

Waterloo, Ontario, Canada, 2012

AUTHOR’S DECLARATION

I hereby declare that i am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners. I understand that my thesis may be made electronically available to the public.

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ABSTRACT

Maintaining a functioning road network is a challenge in today's society due to the financial restrictions faced by all levels of government. A means of determining how to efficiently spend their limited funding must be found. In addition, the concept of sustainable development is rapidly growing in today's world pressuring municipalities towards operating in a more socially and environmentally friendly manner. Sustainability is broken down into three aspects which are economical, social and environmental. A truly sustainable pavement satisfies its functional requirements while aiding social and economic development and minimizing negative environmental impacts

In response to the growing sustainability trend, the City of Markham is committed to incorporating sustainability into their daily operations. This thesis is the result of a research project with the City of Markham which is directed at incorporating sustainable practices into pavement engineering. The objective of this project is to provide a practical framework for incorporating pavement sustainability best practices into the pavement engineering operations at the City of Markham.

This practical framework is developed through the completion of four primary objectives. The first main objective involves the completion of a comprehensive literature review that identifies and reviews the state-of-the-art sustainable pavement best practices. This literature review is divided into five pavement related categories which examine: materials, design and construction techniques, maintenance and rehabilitation techniques, sustainability evaluation systems and carbon footprinting. The second objective involves the quantification of the environmental, economic and carbon footprint impacts of the reviewed pavement best practices; this evaluation is conducted using PaLATE. PaLATE is an excel based software developed at the University of California for evaluating the economical and environmental impacts of various pavement technologies. The third objective involves the utilization of GreenPave for evaluating the environmental friendliness of the analysed pavement best practices. The green discounted life cycle cost (GDLCC) is calculated to include the economic aspect of sustainability. The final objective involves the development of project and network level frameworks. These two frameworks are connected which forms the final framework for incorporating sustainability into City of Markham's pavement engineering operations. Guidelines for the proper utilization of the developed framework are provided.

Through the completion of the literature review it is concluded that there is a wide variety of sustainable pavement technologies that range from project design to pavement decommission. PaLATE analysis results indicate that warm mix asphalt and full depth reclamation are the most environmentally friendly construction and rehabilitation techniques, respectively. Including recycled asphalt pavement (RAP) within pavement mix designs reduces both costs and environmental impacts. Excluding microsurfacing, full depth reclamation was the least expensive rehabilitation technique while hot mix asphalt with RAP was the cheapest construction technique.

The same initial construction and rehabilitation techniques are evaluated using the GreenPave rating system. Pervious concrete scored the highest rating under the initial construction category with warm mix asphalt a close second. Cold in place recycling, cold in place with expanded asphalt and full depth reclamation all scored the highest under the rehabilitation category. In the future, the City of Markham may wish to alter the GreenPave rating system to be more reflective

of municipal practices as the current version of GreenPave is weighted more heavily on high volume roads. To include the economical aspect, the green discounted life cycle cost (GDLCC) is calculated for all techniques. Hot mix asphalt with RAP and full depth reclamation resulted with the lowest GDLCC in the construction and rehabilitation categories, respectively.

Finally, the recommended project and network level frameworks for incorporating sustainability into the pavement engineering practices at the City of Markham are proposed. On the project level, GreenPave evaluation and project level GDLCC aid decision makers in determining the most sustainable project alternative. On the network level, a pavement management system (PMS) serves as the platform. The role of a PMS is to provide recommendations on when and where rehabilitation is required and which rehabilitation technique is the most sustainable. The cost effectiveness and network level GDLCC indicators also aid pavement engineers in making network level decisions. The project and network level frameworks are connected to provide a complete pavement management framework for incorporating sustainability.

The framework provides economic benefits by increasing the effectiveness of budget allocation; this is accomplished by maximizing the overall condition index gained to dollar spent ratio. The environmental benefits of this framework include the minimization of harmful gas emissions, project carbon footprints and energy and water consumption. The social issues of pavement projects are unique to each case and therefore must be addressed case by case. A common starting point when addressing these issues is provided.

ACKNOWLEDGEMENTS

Genuine thanks are extended to the following individuals who provided valuable time, effort and data to aid in the completion of this project.

- Dr. Susan Tighe, PhD, PEng, Professor and Director of Centre for Pavement and Transportation Technology, University of Waterloo
- Mr. Paul Ingham, CET, Director in Operations Department, City of Markham
- Mr. Robert Penner, MASc, PEng, Supervisor in Asset Management Department, City of Markham
- Mr. Mike Brady, r.c.j.i, C.R.S., Supervisor in Operations Department, City of Markham
- Mr. Morgan Jones, Manager in Road Operations Department, City of Markham
- Mr. Peter Loukes, Director in Operations Department, City of Markham
- Mr. Mehran Kaffi, Candidate for Masters of Applied Science, University of Waterloo
- Ms. Samantha Pinto, Candidate for Masters of Applied Science, University of Waterloo

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Chapter 1
INTRODUCTION

1.1. Research Rationale

Maintaining proper roadway infrastructure is a major contributor to the quality of life experienced by local residents. Without an efficient functioning road network, residents would be unable to travel quickly and efficiently. Roads must be properly constructed and maintained throughout their service lives to ensure they are providing the required levels of service. Maintaining a functioning road network is a challenge in today's society due to the financial restrictions faced by all levels of government. A means of determining how to efficiently spend their limited funding must be found.

Sustainable development was originally defined by the World Commission on Environment and Development in 1987 as "development that meets the needs of the present without compromising the ability of future generations to meet theirs" [United Nations, 1987]. Sustainability is divided into several different categories which include economy, social and environment. The economic aspect of sustainability deals with maximizing cash flow efficiency, the social aspect deals with maximizing user satisfaction and the environmental aspect aims to minimize environmental impacts. A truly sustainable pavement satisfies its functional requirements while aiding social and economic development and minimizing the negative impacts on the environment.

The concept of sustainability is gaining momentum in today's world. However, if it is to be incorporated there is a need to quantify the sustainable elements in a clear and simplified manner. The transportation sector is lagging behind the buildings and energy sector in terms of sustainability metrics and certifications. The leadership in energy and environmental design (LEED®) was developed by the United States Green Building Council and is an internationally recognized certification system of green buildings [USGBC, 2011]. There are similar systems available within the transportation sector such as GreenLITES and Greenroads; however none of these systems are internationally recognized. The objective of these systems is to provide a framework for incorporating sustainable best practices into the operation of businesses.

1.2. Scope and Objectives

The City of Markham is committed to incorporating sustainability into their daily operations and is already using sustainable technologies such as Recycled Asphalt Shingles (RAS), Cold In-Place Recycling with Expanded Asphalt Mix (CIREAM), microsurfacing and Full Depth Reclamation (FDR). The City of Markham is currently working on a project called "Quantifying Pavement Sustainability". This research is a result of a joint effort between the City of Markham and the University of Waterloo, Centre of Pavement and Transportation Technology (CPATT). The project began in September 2010 and is scheduled to be completed in August 2012. The main objective of this project is to provide a practical framework for incorporating pavement sustainability best practices into the pavement engineering operations at the City of Markham. This thesis presents the findings of this project.

1.3. Thesis Methodology

This thesis involves the completion of four primary objectives. The first main objective involves the completion of a comprehensive literature review that identifies and reviews the state-of-the-art sustainable pavement best practices.. The second objective involves the quantification of the environmental, economic and carbon footprint impacts of the reviewed pavement best practices; this evaluation is conducted using PaLATE.. The third objective involves the utilization of GreenPave for evaluating the environmental friendliness of the analysed pavement best practices. The green discounted life cycle cost (GDLCC) is calculated to include the economic aspect of sustainability. The final objective involves the development of project and network level frameworks. These two frameworks are connected which forms the final framework for incorporating sustainability into City of Markham's pavement engineering operations. Guidelines for the proper utilization of the developed framework are provided.

1.4. Thesis Organization

This thesis consists of 7 chapters which are displayed in Table 1.1, the contents of each chapter are explained as follows:

Chapter one provides an introduction to the thesis and is divided into four sections which are research rationale, scope and objectives, thesis methodology and thesis organization.

Chapter two provides a comprehensive literature review that identifies and reviews the state-of-the- art sustainable pavement best practices. This literature review is divided into five categories which examine materials, design and construction techniques, maintenance and rehabilitation techniques, sustainability evaluation systems and carbon footprinting.

Chapter three utilizes PaLATE for quantifying the environmental, economic and carbon footprint impacts of the reviewed sustainable pavement best practices.

Chapter four identifies GreenPave as the sustainability rating system that is most applicable to the City of Markham. GreenPave is then utilized in evaluating the environmental friendliness of the pavement best practices. To include the economic aspect of sustainability in this evaluation, the green discounted life cycle cost is calculated for all best practices.

Chapter five develops a practical framework for incorporating sustainability into the project level and network level pavement engineering operations at the City of Markham. A link between the developed network level and project level frameworks is proposed.

Chapter six provides guidelines for the proper utilization of the developed frameworks.

Chapter seven summarizes the main conclusions and recommendations of this thesis.

Table 1.1 – Summary of Project Objectives

Chapter 1: Introduction
Chapter 2: Literature Review
Chapter 3: Quantifying Typical Savings
Chapter 4: Sustainability Measurement Tools Evaluation
Chapter 5: Network and Project Level Framework Development
Chapter 6: Anaylsis Guidelines
Chapter 7: Conclusions and Recommendations

Chapter 2
LITERATURE REVIEW

2.1. Introduction

The concept of sustainability is a major issue in today's world and the transportation sector has responded accordingly. There are a large variety of different sustainable materials, designs, construction and maintenance best practices currently being researched. There is also a need to quantify these sustainable pavement best practices and researchers are currently aiming to develop tools which assist in addressing this need.

A literature review evaluating the state-of-the-art pavement best practices in terms of sustainability was conducted. This literature review is divided into the following categories: materials, designs and construction techniques, maintenance and rehabilitation techniques, carbon foot printing and sustainability evaluation tools. Table 2.1 displays the items included within the literature review. The objective of this literature review is to identify and review the state-of-the-art sustainable pavement best practices. The environmental, economical and carbon footprint impacts of these best practices are analysed in Chapter 3.

Table 2.1 – Literature Review Items

Materials	Design and Construction Techniques	Maintenance and Rehabilitation Techniques	Carbon Foot Printing	Sustainability Evaluation Tools
Recycled Concrete Aggregate (RCA)	Perpetual Pavement	Cold In-Place Recycling	Carbonation Curing	LEED®
Reclaimed Asphalt Pavement (RAP)	Warm Mix Asphalt	Cold In-Place Recycling with Expanded Asphalt	Supplementary Cement Materials	GreenLITES
Recycled Asphalt Shingles (RAS)	Porous Asphalt Pavement	Full Depth Reclamation	ECOAGE, Quantifying Greenhouse Gas Emissions	Greenroads
Recycled Glass	Quiet Asphalt Pavement	Microsurfacing	Life-Cycle Assessments	GreenPave
Recycled Ceramic Whiteware	Pervious Concrete Pavement	Diamond Grinding		Sustainable Highways Self-Evaluation Tool
Recycled Crumb Rubber	Permeable Interlocking Concrete Pavers	Precast Concrete Panels		Envision
Interlocking Concrete Pavers	Quiet Cncrete Pavement	Concrete Rubblization		
Supplementary Cement Materials	Two Lift Concrete Construction	Solar Heat-Blocking Pavement		

2.2. Materials

Construction materials can be expensive and potentially in limited supply. Therefore, it is crucial that the materials available are used efficiently and effectively. The recycling, reusing and reclaiming of asphalt and concrete pavement is vital to advancing pavement sustainability. Including innovative materials such as recycled asphalt shingles or crumb rubber within pavement mix designs can improve performance and reduce the demand for virgin materials. Therefore, the materials contained in pavement mixes must be in included in the quantification of pavement sustainability.

2.2.1. Recycled Concrete Aggregate

Ontario is currently using aggregates faster than it is being made available; for every three tonnes used only one tonne is being replaced. Therefore it is vital to find new and innovative sources of aggregate. Recycled Concrete Aggregate (RCA) is a pavement application where concrete is crushed and graded and reused in new concrete. The demolished concrete comes from sidewalk, curb and gutter instead of virgin material. It is generally unacceptable to recycled concrete from other applications such as bridges or buildings since there is a high variability in concrete materials. However, on-going research shows that this could possibly be used. Sidewalks, curbs and gutters are designed to satisfy the Ontario Provincial Standard Specification (OPSS) requirements [Chan, 2010].

Potential benefits of RCA include conservation of virgin material, cost savings and reduced concrete waste and energy consumption. Several barriers must be overcome before RCA as an aggregate source becomes widely accepted. Concrete crushers must be purchased and maintained which represents high initial investments. Another problem is the large amounts of fine aggregate produces from the crushing process, which must be either be disposed or have an alternative use found. There is also a lack of knowledge of how RCA may adversely influence the new pavements performance [Smith, 2008]. However, it should be noted as agencies begin to use this material, the cost will be reduced and it will be readily available.

Researchers have found that as the amount of RCA included in mix designs increases, the pavement durability decreases. Mixes containing RCA are also stiffer and tend to lose workability faster than mixes containing only virgin materials. This occurs because RCA is a highly absorptive and porous material therefore it is recommended that RCA be pre-wetted before mixing. Researchers have found mixed results for other pavement properties including compressive and flexural strength and freeze-thaw resistance. This is likely due to the high variability in RCA material properties. Further RCA research is required to fully understand the impact and benefits of including RCA in mixes [Smith, 2008].

The Centre for Pavement and Transportation Technology (CPATT) at the University of Waterloo partnered with the Cement Association of Canada (CAC) and Dufferin Construction has placed a test section containing four different RCA mix designs. The mix designs contain 0%, 15%, 30% and 50% RCA. Initial studies have found that the four test sections have no significant performance differences [Smith, 2008].

2.2.2. Reclaimed Asphalt Pavement

Asphalt pavement is a highly recycled material in road applications and is one of the most recycled materials in Canada. Like RCA, Reclaimed Asphalt Pavement (RAP) reduces the demand for virgin material, reduces construction waste, saves costs and energy and can easily be stockpiled for future use. RAP can be used in both hot mix pavement designs or as granular material depending on specifications and requirements [Chan, 2010]. When processed properly, pavements containing RAP perform equally well when compared to pavement containing only virgin material. The most common method for recycling asphalt pavement is called Cold In-Place Recycling (CIR). RAP is combined with emulsified asphalt and virgin aggregate, without heat and on site to produce new cold mix asphalt [Chan, 2010].

The Specific Pavement Studies 5 (SPS-5) in the United States Long Term Pavement Performance program (LTPP) was designed the evaluate the effect of overlay rehabilitation on common distresses including IRI, rutting, ravelling fatigue cracking, longitudinal cracking and transverse cracking. Eighteen overlay test sections located around North America were evaluates; one of the overlay characteristics evaluated was the use of 30% RAP. The test concluded that including 30% RAP within the overlay does not adversely affect performance; in some cases the overlay containing RAP performed better than its traditional mix counterpart [West, 2011].

In Ontario, the use of Reclaimed Asphalt Pavement is governed by OPSS 1150. It states that up to 20% RAP is allowed for surface course mixes, 20% is allowed for medium duty binder course mix and 40% is allowed for binder mixes by mass. In certain circumstances, up to 50% RAP by mass is allowed for binder mixes but the contract administrator's written approval is required. RAP that is contaminated by harmful materials is not to be used [OPSS 1150, 2010]. However, Ontario contractors are usually reluctant to use more than 20% RAP by mass due to a difference in asphalt cement gradation if more than 20% is used [Chan, 2010]. Table 2.2 displays the maximum RAP allowance in HMA pavement based on the design EASLs of the pavement in question.

Table 2.2 – Ontario's Maximum RAP Allowance [Raymond, 2010]

Traffic Category (Design ESALs)	Binder Course 150 mm or More Below Pavement Surface	Binder Course Within 150 mm of Pavement Surface	Surface Course Excluding SMA
< 3 million	40%	40%	20%
3 to 30 million	40%	40%	20%
≥ 30 million	40%	20%	20%

The United States Federal Highway Administration (FHWA) fully supports the use of RAP within their highway projects. The FHWA states that HMA containing RAP "generally age more slowly and are more resistant to the action of water than conventional HMA" [Raymond, 2010]. The FHWAs objective is to increase the number of highway projects utilizing RAP and to increase the amount of RAP used in these projects. A recent study conducted in Manitoba evaluated the resistance of HMA mixtures containing up to 50% RAP to thermal cracking and moisture damage. The test concluded these mixtures resulted in acceptable levels resistance to moisture damage and thermal cracking [Loria, 2011].

2.2.3. Recycled Asphalt Shingles

There are two types of shingles used in pavement applications; the first is Recycled Asphalt Shingles (RAS) and the second is manufactured asphalt shingle tabs. Manufactured asphalt shingle tabs are obtained from the shingle manufacturing process and therefore have more a more uniform material consistency that RAS [Chan, 2010]. RAS are obtained from decommissioned shingle rooftops or the shingle insulation trimmings. RAS contains approximately 30% asphalt cement by mass weight; the other material components of RAS are hard rock granules, fillers and fibres [Tighe, 2008]. RAS typically has higher concentrations of asphalt cement because the granules within RAS are worn out by weathering. Many Departments of Transportation limit the amount of RAS allowed in mix designs; RAS replaces fine aggregates in hot mix asphalt.

Potential benefits of RAS include a reduction of virgin material consumption, minimization of shingle waste volumes and cost savings. Researchers have found that including RAS within mix designs can improve pavement performance; more specifically can increase resistance to rutting and low temperature cracking. A major issue with using RAS is the need to remove foreign contaminants, such as nails and felt overlay prior to utilization [Tighe, 2008].

Several studies performed by CPATT in partnership with Miller Paving Limited and Materials Manufacturing Ontario (MMO) tested the usage of RAS in asphalt. The first study evaluated the performance of Superpave 19C containing RAS. Five mixes were tested containing different combinations of virgin aggregates, RAP and RAS. The study tested the dynamic modulus, resilient modulus, rutting and low temperature cracking of the five mix designs. The study showed that including RAS in mix designs can increase pavement rutting and thermal crack resistance [Tighe, 2008]. Another study evaluated the performance of pavements containing RAP and RAS based on the following criteria: dynamic modulus, resilient modulus, tensile strength, TSRST and rutting. The follow five mix designs were tested:

- Mix 1 – HL8 (control)
- Mix 2 – HL8 with 20% RAP
- Mix 3 – HL8 with 20% RAP and 1.4% RAS
- Mix 4 – HL8 with 20% RAP and 3.0% RAS
- Mix 5 – HL8 with 3.0% RAS

Laboratory tests concluded the mixes containing RAS performed at similar levels to the control mix. The City of Markham constructed a pavement containing 1.5% RAS which is performing very well after three years in service [Ddamba, 2011].

2.2.4. Recycled Glass

Recycled glass is a relatively new form of aggregate being researched. Researchers have found that glass can be continuously recycled and will never lose its original properties making it a perfect aggregate for pavement. In addition, the strength of crushed glass is comparable to the strength of rock [Chan, 2010]. Using recycled glass as aggregate material has a number of benefits including reduced waste, cost savings and virgin material conservation. The main problem preventing widespread use of recycled glass is that it usually contains contaminants such as sugar, paper and cardboard. These contaminants will adversely affect pavement performance; sugar for example is known to react with Portland cement preventing glass from being used as a concrete aggregate substitute. Recycled glass is not suitable for use in surface courses due to its weak adhesion with asphalt cement which results in ravelling [Chan, 2009].

New Zealand has been testing recycled glass as an aggregate substitute since 2005 and their results have been promising. Current New Zealand specifications allow recycled glass to replace virgin aggregate up to 5%. “A visual assessment of performance to date shows no difference between the sections of road constructed with recycled glass and the virgin aggregate sections” [Fulton, 2008].

2.2.5. Recycled Ceramic Whiteware

Recycled ceramic whiteware usually consists of crushed toilets and are typically used as a substitute aggregate material. The benefits of recycling ceramic whiteware are a reduction in virgin material consumption and waste minimization. However, several major obstacles must be overcome before the practice becomes wide spread. When crushed, ceramic whiteware fragments tend to have a long and flat shape which is not desirable for compaction. Two additional problems are material availability and the economic feasibility of cleaning the ceramic whiteware [Chan, 2010].

2.2.6. Recycled Crumb Rubber

Due to the availability of old disposed tires; research has been conducted in the utilization of scrap tire fragments as a pavement aggregate substitute. Crumb rubber has been use is asphalt mixes since the mid 1960's when it was first used by the City of Phoenix for chip sealing [Cheng, 2011].

Including crumb rubber within asphalt pavement has been proven to increase pavement flexibility resulting in a crack reduction of approximately 20%. Traffic noise levels are also reduced due to the reduction in cracking [Cheng, 2011]. Researchers agree that including crumb rubber within asphalt pavement decreases the pavement susceptibility to rutting, fatigue and temperature. In addition, using crumb rubber reduces waste and the need for virgin materials. However, crumb rubber tends to decrease the mixture workability resulting in the need for higher mixing and compaction temperatures which significantly increases costs. The availability and high cost associated with crumb rubber production are two other limitations to wide spread use. Another limitation to crumb rubber is its bonding strength with asphalt cement; this weak bond leads to ravelling problems [Cheng, 2011].

A recent study has proposed including crumb rubber within warm mix asphalt mix designs. Since warm mix asphalt is produced under lower temperatures than traditional hot mix asphalt, the major cost limitation of using crumb rubber in tradition asphalt is addressed. "While temperatures aren't reduced as much as WMA devoid of rubber, the temperatures can be reduced to a range that makes the use of rubber more cost effective" [Cheng, 2011].

2.2.7. Interlocking Concrete Pavers

Interlocking concrete pavers (ICP) are individual concrete pavement segments placed in tight formation to provide an alternative pavement for concrete and asphalt. Concrete pavers are installed manually or mechanically on subbase, granular base, or asphalt/concrete base and finished with joint sand. Common applications of interlocking concrete pavers include parking lots, walkways, rural and urban roadways, crosswalks and bus terminals. OPSS 355 covers the installation specifications of concrete pavers for pavement, sidewalks boulevards and medians. The spacing between adjacent pavers must be between two to five millimetres. OPSS 355 states that interlocking concrete pavers should not be used for roads where traffic speeds exceed 70km/h [OPSS 355, 2006]. Interlocking concrete pavers have the ability to support large loads as proven by a study completed by the Interlocking Concrete Pavement Institute (ICPI) at the Hong Kong International Airport. The pavers were placed on top of an asphalt base to create a fuel resistant surface at the aprons [Chan, 2010]. Another advantage of concrete pavers is their ability to resist differential subgrade settlement. The ICPI conducted another study in North Bay Ontario. The installed pavers required no maintenance up to 12 years after construction proving interlocking concrete pavers perform well under cold climates. Concrete pavers are not widely used because high volumes of traffic will destroy the pavers over time [Chan, 2010].

2.2.8. Supplementary Cementing Material

Supplementary Cementing Materials (SCM) are materials added to concrete mixes to enhance the properties of concrete; the chosen SCM depends on the desired property. Not only does including SCMs in cement mixes enhance its properties but it also prevents these by-products from being land-filled. Possible property enhancements include permeability reduction, strength improvement and feasibility improvement. The three common SCMs are fly ash, ground granulated blast furnace slag (GGBFS) and silica fumes. These materials are by-products of other processes therefore using them in concrete mixes is a sustainable practice. SCMs are classified into two categories which are hydraulic and pozzolanic. Both types form cementing compounds but hydraulic SCMs react with water while pozzolanic SCMs react with Portland cement [Thean seng, 2011]. Table 2.3 provides a summary of the three most common SCMs.

Fly ash is the most commonly used SCM because of its availability and low cost; it's a fine residue produced when coal impurities are combusted. Benefits of fly ash include increased durability and workability, reduced hydration heat and increased resistance to certain chemicals (sulphate attack and alkali silica reaction) [Thean seng, 2011]. Fly ash specifications are available under the OPSS 1350; it states that concrete mixes shall contain no more than 10% fly ash [Chan, 2010].

GGBFS is a by-product of the steel industry; it's formed when hot iron blast furnace slag is rapidly cooled when submersed in water. GGBFS is fine residue with a crystal formation that readily hydrates like Portland cement. A blend of Portland cement, fly ash and GGBFS is being used for many applications; however GGBFS is not as readily available as fly ash. Research has shown that for optimal 28 day strength 50% GGBFS should be used. While concrete strength development is initially lower (1-5 days), the final strength of concrete containing GGBFS is higher than concrete containing only Portland cement. Other GGBFS benefits include, reduced hydration heat, increased workability, reduced water demand, and increased flexural strength. GGBFS does present disadvantages including, increases necessity of proper curing, increased shrinkage cracking, increased setting times and reduced performance at low temperatures [Thean seng, 2011].

Silica fume is a by-product of the semiconductor industry; it forms when quartz with wood chips and coal or coke is placed in an electric arc furnace. Silica fume is a pozzolanic material with spherical particles that are approximately 100^{th} the size of cement grains. The ideal silica fume concentration recommended by researches is 5-10% by mass of cement. Silica fumes are typically used for high strength concrete application and areas that experience high abrasion or corrosion. Advantage of silica fumes include increased strength, increased durability, and the filling of voids created by cement particles. Disadvantages include higher cost, difficulty in handling (easily airborne) and increased water demand [Thean seng, 2011].

Table 2.3 – SCM Summary Table [Thean seng, 2011]

Material	Fly Ash	GGBFS	Silica Fumes
Description	Produced when coal impurities are combusted; most common SCM due to its availability and low cost	A by product of steel industry; formed when hot blast furnace slag is rapidly cooled when submersed in water	By product of semiconductor industry; pozzolanic material with spherical particles approximately 100th the size of cement grains
Advantages	Increased workability, durability, chemical resistance and reduced heat of hydration	Increased final strength, flexural strength and workability and decresed water demand and heat of hydration	Increased strength, durability and resistance to abrasion; also fills viods created by cement particles
Disadvantages	May only be utiltied up to 10% fly ash in concrete mixtures	Increased shrinkage cracking, setting times and reduced performance at low temperatures	High costs, difficulty in handling and increased water demand.

2.3. Design and Construction Techniques

A truly sustainable pavement must exhibit sustainable qualities throughout the entire life cycle. Therefore while material selection is a significant contributor to the sustainability of pavement projects, pavement design and construction must also be looked at. This section reviews the different sustainable pavement designs and construction techniques.

2.3.1. Perpetual Pavement (Long-Life Pavement)

The concept of perpetual pavement was originally introduced by the Asphalt Pavement Alliance in 2000. Perpetual pavement is defined as "an asphalt pavement designed and built to last more than 50 years without requiring major structural rehabilitation or reconstruction, and needing only periodic surface renewal in response to distresses confined to the top layer" [Newcomb, 2010]. It's designed to eliminate the need to repair the bottom layer of pavement. In theory, perpetual pavement reduces the life cycle cost of pavements since it avoids expensive deep pavement maintenance and reconstruction. User delay is also minimized since only minor surface maintenance is required which can be completed during off peak hours. Perpetual pavements are also environmentally friendly since they consume less material throughout their life cycles [Newcomb, 2010].

CPATT and the MTO are currently conducting a research study evaluating the performance of perpetual pavement on Highway 401. The test section is divided into three segments; perpetual pavement with a rich bottom mix, perpetual pavement without a rich bottom mix and a conventional control section. The perpetual pavement design consists of multiple pavement layers each designed to address one or more distress including rutting, fatigue cracking and low temperature cracking. Recycled asphalt pavement was utilized in all layers, this proved to enhance the pavement mechanical properties and maximize the efficiency of material use. A life cycle cost analysis has been conducted comparing the life cycle costs of perpetual pavement to conventional pavement. This research shows that even with larger initial construction costs, perpetual pavement still results with a lower life cycle cost due to minimized rehabilitation requirements. Researchers continue to monitor the test section; however, initial results indicate both economical and environmental savings [El-Hakim, 2012].

2.3.2. Warm Mix Asphalt

Warm mix asphalt (WMA) is a type of asphalt where the production and placement temperatures are lower than conventional asphalt. For an asphalt to be considered warm mix its production and placement temperature must be less than 135°C. Potential benefits of using warm mix asphalt include a reduction in fuel usage, reduction in emissions, increased paving seasons and improved working conditions. There are a variety of different warm mix additives available; these additives fall under three categories which are organic or wax, chemical or water for foaming. These additives are added while the asphalt is being manufactured in the plant [Cheng, 2011].

CPATT in partnership with McAsphalt Industries Limited is conducting research evaluating the structural and environmental aspects of warm mix asphalt. Resilient modulus and dynamic modulus testing has revealed no differences between WMA and traditional HMA. Evotherm, a chemical additive, was used for this study. Potential benefits of Evotherm include improved coating, workability, compaction, adhesion and emulsification [Esenwa, 2011]. Laboratory results indicated WMA containing Evotherm can be produced at 60°C; which results in fuel savings of approximately 55% [Chan, 2010].

A recent study conducted in Ohio compared the performance between WMA containing RAP and tradition HMA. Emissions and temperatures were monitored during the production and placement of both WMA and HMA test sections. To compare pavement performance, rutting and roughness tests were conducted during the first four years of service. Core samples were also taken from both test sections. The results proved the WMA resulted in a significant reduction in temperature and emissions during both production and placement when compared to traditional HMA. WMA was also observed to have a higher in-place density than its HMA counterpart. The core sampled proved than WMA had higher indirect tensile strength than HMA; however this tensile strength then increased faster in HMA. After four years, neither test section showed any signs of rutting; both sections had similar IRI values [Nazzal, 2011]

2.3.3. Porous Asphalt Pavement

Porous asphalt pavement allows fluids to pass directly through the pavement structure and into the ground. It offers an alternative technology for storm water management by reducing or eliminating runoff. The only difference between traditional asphalt pavement and porous asphalt pavement is a reduction in the amount of fine aggregates which increases permeability. A layer of open graded stone is located beneath the porous pavement surface allowing water to quickly infiltrate the surrounding soil. Recommended applications for porous asphalt pavement include parking lots and low volume roads [Schaus, 2007].

Potential benefits of porous asphalt pavement include reduced traffic noise, improved skid resistance, reduced groundwater contamination through runoff, improved pedestrian and driver safety due to reduced spray and reduced potential for black ice. Studies have shown that porous asphalt pavement has the potential to reduce spray during rainfall by 95% [Chan, 2010]. However the major concern with porous pavement is clogging. Debris entering the pavement structure reduces the pavements ability to swallow water which defeats its purpose. Water trapped within the structure expands when frozen causing a high likelihood of ravelling. Therefore it is recommended that the voids be cleaned during the fall season to minimize the probability of ravelling. Another limitation of porous pavement is a reduction in structural strength.

A recent study conducted at the National Centre for Asphalt Pavement test track in Alabama evaluated the noise reduction ability of porous pavements. Acoustic measurements were taken at twenty two different pavement sections including five that were porous pavements. Porous pavements were found to reduce traffic noise in two different ways. The noise generated at the tire pavement interface was reduced, which is the dominant source of traffic noise at speeds greater than 50km/hr. Porous pavement can also reduce noise by relieving the air-pumping noise mechanism. Double layer porous pavements were found to produce the lowest on-board sound intensity levels [Donavan, 2011].

2.3.4. Quiet Asphalt Pavement

Traffic noise is a huge problem for urban areas; traditional methods of managing noise include barriers and earthberms that obstruct sound. These methods do not solve the noise problem and in a lot of cases are infeasible. Traffic noise is generated from three sources which are vehicle engines, aerodynamics and tire-pavement interaction. Studies have found when speeds exceed 50km/h, the dominant noise source is the tire-pavement interaction and that pavement surface characteristics play a major role in noise generation. Traffic noise generation was observed to increase as vehicle speed and size increased. Several examples of noise reducing asphalt pavements proven to work are thin gap graded asphalt, porous asphalt pavement and stone mastic asphalt [Woldemariam, 2011] Europeans follow strict pavement specifications to achieve quiet asphalt pavements since often times enough space for barriers is not available.

In 2007, CPATT in partnership with the Region of Waterloo conducted a study on the sound mitigation ability of four different surface courses. These mixes were Rubberized Open Friction Course (rOFC), Rubberized Open Graded Course (rOGC), Stone Mastic Asphalt (SMA) and HL-3 as the control. The results proved that even though its sound mitigation ability decreased after the first year, the optimal sound mitigating mix was rOGC. The SMA mix's sound mitigation ability was observed to increase after the first year but did not exceed rOGC's ability. The study included a life cycle cost analysis to determine the economic feasibility of the four mixes. The result indicated that while HL-3 performed the worst in terms of sound mitigation, it was the most economically feasible mix. The least economically feasible mix was rOFC [Leung, 2007].

To minimize noise generated from the tire-pavement interaction, European countries utilize porous asphalt and thin graded (gap graded) asphalt mixes. The gradation of aggregates used within their mixtures is very specific and is specified as a maximum and minimum percent of aggregates passing certain sieves. These percentages and sieves are dependent on a variety of factors including traffic conditions and environmental factors. The binders and additives used are also specified; for porous asphalt the paving grade bitumen grades must range between 35/50 and 250/350. For thin graded asphalt, the bitumen grades must range between 36/50 and 160/220. The minimum binder contents of porous asphalt and thin graded asphalt are 3% and 5% respectively. Noise levels were initially observed to drop by 3-5 dB but as the pavement aged, this number dropped to approximately 1dB after several years [Woldemariam, 2011].

In 2006, Denmark introduced the SRS system (noise reducing surfacing) in an effort to introduce noise reducing pavements into the market. The SRS system is a certification system which requires the contractor to "produce documentation proving the noise reducing properties of a specific SRS by comparing measured values with a national reference value" [Bendtsen, 2010]. The system contains three levels of noise reduction in relation which are:

- A – very good noise reduction (X>7.0 dB)
- B – good noise reduction (5.0<X<7.0 dB)
- C – noise reduction (3.0<X<5.0 dB)

The SRS system has succeeded in bring noise reducing pavements to the Danish market. Using noise reducing asphalt on new roads and in road maintenance is now common practice in some of Denmark's larger cities [Bendtsen, 2010].

2.3.5. Pervious Concrete Pavement

Pervious concrete pavement is a sustainable alternative to traditional concrete pavements. The objective of pervious concrete is to allow water to drain through the pavement structure. Pervious concrete mixes are similar to traditional mixes; the difference is that it contains reduced amounts of fine aggregate and is open graded. These differences create voids which allow storm water to enter the pavement structure. Benefits of pervious concrete include reduced need for storm water management systems and the elimination of runoff. Eliminating runoff is beneficial to the environment by reducing pollution and preventing heated water from entering the local water systems. Pervious concrete pavements have been regularly used in areas with warmer climates. The greatest challenge to successfully implementing pervious concrete in colder areas such as Canada is freeze-thaw. Water trapped within the pavement structure expands when frozen, increasing the likelihood of ravelling. It is recommended that permeability restoration maintenance be performed during the fall season to prevent water from being trapped during freeze-thaw cycles [Henderson, 2011].

There are three major functional considerations for pervious concrete related to winter maintenance which are ravelling or coarse aggregate loss, ensuring adequate structural capacity and preventing clogging. Air void clogging reduces pavement permeability threatening its key objective. Several maintenance techniques designed to increase permeability are sweeping, power washing and vacuuming. These techniques do increase permeability but never to its original condition. The lack of structural capacity prevents pervious concrete pavements from being applied on roads with heavy traffic loads. Therefore recommended uses for pervious concrete are parking lots, low volume roads, sidewalks and driveways [Henderson, 2011].

A recent study in Europe analysed the performance of two different types of pervious concrete pavements. The difference between the two pavements is the size of the concrete aggregate. One mixture contained fine aggregates which lead to a better distribution of air voids throughout the pavement structure. The other mixture contained course aggregates which created larger but sparser air voids. Each pavement structure was tested based on its deterioration due to calcium leeching. Due to the uniform distribution of voids throughout the fine aggregate mixture, it was observed that water moved through the structure more evenly. This resulted in a uniform deterioration of the structure; finer aggregates also encourage a thicker mortar film. In the course aggregate mixture, it was observed that the larger and sparser distribution of voids lead to localized deterioration. Therefore, while high permeability is the primary goal pervious concrete, it is recommended that smaller aggregate sizes be chosen for minimizing the effects of calcium leeching [Kringos, 2011].

2.3.6. Permeable Interlocking Concrete Pavers

Permeable Interlocking Concrete Pavers (PICP) are similar to ICP except they allow water to pass directly through the paver structure. The main objective of PICP is to allow water to pass through the paver structure and therefore reduce runoff and water entering the storm water system. There are four different kinds of PICP which are concrete grid pavers, widened permeable joints, porous concrete unit and interlocking shapes with openings. Concrete grid pavers have a large opening in the middle which allows grass to grow and water to penetrate the paver structure. Widened permeable joints contain spaces between the individual pavers which allow water to pass through. Porous concrete units are the only PICP where the pavers themselves are permeable; they are manufactured with no fine aggregates to allow water to pass directly through the pavers themselves. Interlocking shapes with openings leaves gaps between different adjoining paver shapes to allow water penetration [ICPI, 2008] [Chan, 2010].

A major benefit to using PICP is that they are centrally manufactured at plants under controlled environments; therefore paver characteristics are uniform. Also damaged pavers can be replaced on an individual basis making maintenance cost effective and fast. Concrete pavers are precast therefore there is no curing time required at the end of construction [ICPI, 2008] [Chan, 2010]. The drawback to PICP is that they cannot be used on high volume roads since repeated vehicle exposure will destroy the pavers over time.

2.3.7. Quiet Concrete Pavement

Traffic noise generated on concrete pavements can be mitigated through the use of surface texturization methods including diamond grinding (whisper grinding) and longitudinal tining. Whisper grinding is a new diamond grinding technique studied in the State of Arizona. The technique involves grinding narrow grooves on the pavement surface parallel to the vehicles movement direction. These pavements were proven to be the quietest and smoothest concrete pavements in Arizona. Longitudinal tining is similar to whisper grinding except the grooves tend to be more widely spaces [Ahammed, 2008].

Two techniques currently used in Europe are exposed aggregate and double layer pervious concrete. Exposed aggregate has proven to not be as effective in mitigating noise as originally thought; however double layer pervious concrete has proven to be quieter [Ahammed, 2008].

2.3.8. Two Lift Concrete Construction

Two lift concrete construction is a process where concrete pavement is constructed in two layers on the base material. The bottom layer of concrete is thick and contains low quality materials which can include recycled concrete aggregate. This is acceptable since the layer is not exposed to the surface. The top layer of concrete is thin and contains high quality materials to achieve the desired strength, durability, friction, and noise mitigating characteristics of traditional pavement. The objective of two lifts concrete construction is to reduce the demand of virgin material by including recycled material in the bottom layer [Chan, 2010].

The advantage of two lift concrete pavement is the use of lower quality material in the bottom layer. This reduces the demand for virgin material and reduces the amount of concrete waste material. The major limitation of two lifts concrete construction is economic feasibility; construction requires the use of two plants and two sets of paving machines which can dramatically increase costs. However, these additional costs can partly or in some cases entirely be recovered through the use of lower quality and less expensive materials in the lower layer [Cable, 2004].

An experimental two lift concrete road was opened to traffic in Florida in 1978. This road contains a series of two layer concrete sections with different features all placed over a cement treated or granular subbase. These sections consisted of a 75 mm surface layer over a 225 mm lean concrete layer. The control section was the traditional PCC pavement on the cement treated subbase. The performance of all sections was evaluated after 30 years. The control section was observed to exhibit greater amounts of cracking than the two lifts sections and even moderate to severe spalling. The two lift sections constructed over granular subbase performed better than the sections over cement treated subbase. Therefore two lifts concrete construction was concluded to be a sustainable and long lasting pavement design alternative [Greene, 2011].

Another two layer concrete test section was constructed in 2010 at the Minnesota Road Research Facility by the Strategic Highways Research Program (SHRP2). The most challenging part of this project was the concrete mix designs and their onsite delivery. The top layer was a conventional EAC mix while the bottom layer mix was designed with high levels of fly ash and recycled concrete aggregate. Fly ash and RCA were utilized in an attempt to reduce material costs. A major problem encountered with these mix designs was the concrete slump consistency of the bottom layer; the slump test of the delivered concrete ranged between 6.25 to 68.75 mm (the targeted slump was 25 mm). Due to budget constraints project engineers decided to use one batch plant [Tompkins, 2011].

Two concrete pavers were employed during construction for the two different concrete layers. A challenge associated with this design relates to the need to have the top layer of higher quality concrete paved no more than 90 minutes after the bottom layer; this time limit was exceeded on numerous occasions. These delays caused a variety of problems including shrinkage cracking and a potentially inadequate bond integrity between the two layers. For this project, the top layer paver crown was adjusted to add an extra 0.75 inches to both sides of the pavement, making the top layer 1.5 inches wider than the bottom layer [Tompkins, 2011].

2.4. Maintenance and Rehabilitation Techniques

Maintenance and rehabilitation must be carried out for a pavement structure to remain operational throughout its service life. Maintenance techniques are grouped into two categories which are preventative and reactive. Preventative maintenance is performed on pavement prior to distress formation to minimize the likelihood and severity of those distresses. Reactive maintenance is performed because distresses have formed and are required to be fixed. There is a large range of different maintenance and rehabilitation techniques available; this section discusses several of these techniques which have been found to have sustainable elements.

2.4.1. Cold In-Place Recycling

The concept of Cold In-Place (CIP) recycling was originally introduced in Eastern Canada in 1989 [Miller, 2011a]. CIP recycling is based on the principle that the existing asphalt pavement is a source of material. The process is carried out in place where the top 65-125 mm of bituminous material is reclaimed as RAP, transformed into bituminous aggregate, mixed with an emulsion, laid down and compacted; the entire process occurs as one continuous operation. Once the curing period has passed, the recycled layer is surfaced with an asphalt wearing course. The major limitation of CIP is the long and temperature dependant curing time. The surface mix may only be applied after the CIP mix has cured for a minimum of 14 days. Work shall only be carried out if the temperature is greater than 10 °C and the overnight low is greater than 2 °C; written approval must be provided after September 1st [OPSS 333, 2010]. Portland cement may be added to the mixture to achieve rapid curing which allows traffic to be maintained until the asphalt surface coat is applied [Miller, 2011a].

CIP recycling has economic, environmental and performance benefits when compared to traditional pavement rehabilitation techniques. Reduced virgin material requirements minimize expenditures in two ways: material purchasing and material transportation costs. The cold nature of the process reduces energy consumption and minimizes negative environmental impacts. Vehicle fuel consumption is also minimized. The major performance benefit of CIP is its reflective crack mitigation property; "CIP is considered the most effective process to mitigate reflective cracking in a cold climate" [Miller, 2011a]. CIP is preferred over Hot In-Place since it minimizes energy consumption and better mitigates reflective cracking from the base layer [Chan, 2010].

2.4.2. Cold In-Place Recycling with Expanded Asphalt

Cold In-Place recycling with Expanded Asphalt Mix (CIREAM) is exactly the same as CIP except CIREAM utilizes expanded/foamed asphalt to stabilize the existing recycled asphalt pavement instead of highfloat emulsified asphalt. Expanded asphalt is defined as "heated asphalt cement expanded from its normal volume with the addition of water" [OPSS 335, 2009]. Expanded asphalt has a lower viscosity than traditional hot mix asphalt due to the addition of water; this lower viscosity allows the expanded asphalt to better blend with the RAP [Chan, 2009].

CIREAM has two advantages over CIP while maintaining all of its benefits. The binder used within CIREAM results in rapid mixture curing. This allows traffic to resume after only 3 curing days compared to the 14 days required by CIP [OPSS 335, 2009]. The shorter curing time minimizes user delay costs and allows for shorter construction schedules. The second advantage of CIREAM is that expanded asphalt is less susceptible to moisture than emulsified asphalt [Chan, 2009].

2.4.3. Full Depth Reclamation

Full Depth Reclamation (FDR) is a pavement rehabilitation technique where the pavement surface layer and part of the underlying base are pulverized. Stabilizing additives are added to the pulverized pavement for the purposes of restoring strength and uniformity [Shongtao, 2011]. Examples of these additives include asphalt emulsion, expanded asphalt and portland cement. Expanded asphalt significantly reduces the curing duration which has lead to its recent gain in popularity. The pulverized pavement is compacted and reused as granular material on the existing ground. FDR recycles large quantities of material leading to significant environmental and economic benefits. Another benefit of FDR is its resistance to reflective cracking caused by base layer failure. Utilizing expanded asphalt also provides rutting and fatigue cracking resistance [Chan, 2010].

A recent study was conducted by the Minnesota Department of Transportation tested the performance of FDR rehabilitated pavements. Three test sections were constructed on Interstate 94 at the MnROAD test facility in 2008; each test section contained different emulsion contents. The short term performance testing has resulted with no cracking and low rutting (<0.15 inches) in all test sections. The test sections were designed for 3.5 million EASLs in 5 years; future testing will demonstrate FDRs long term performance [Shongtao, 2011].

A case study located in Las Vegas, Nevada demonstrated FDRs time and cost saving potential. A major arterial road requiring reconstruction was rehabilitated using FDR. The city reported costs savings of approximately 30% and a construction period reduction from 120 days to 40 days when compared to traditional reconstruction [Shongtao, 2011].

2.4.4. Microsurfacing

Microsurfacing is a preventative pavement maintenance treatment used for flexible pavements. Microsurfacing is a competitive alternative to traditional surface restoration methods and it extends pavement life by 4 to 8 years on medium to high traffic roads. Microsurfacing is designed to correct pavements which are structurally sound but showing signs of rutting, inadequate pavement cross sections or inadequate surface friction. The applied mixture typically consists of a "polymer-modified cationic emulsified asphalt, mineral aggregate, mineral filler, water and additives" [Miller, 2011b].

According to OPSS 336, there are currently three types of microsurfacing treatment: Type II, Type III modified and Type III. These microsurfacing types have different aggregates and material gradations and are therefore applicable in different situation. Type II microsurfacing is applicable for low volume local roads, arterials and collectors. Type III microsurfacing is used on high volume and speed roads such as highways and freeways. Type III microsurfacing reduces traffic noise and is generally used in lieu of Type III [OPSS 336, 2009].

Microsurfacing is a cost effect preventative treatment which extends the life of pavements. This allows organizations to maintain high quality pavement networks with reduced budgets by eliminating the need for expensive road rehabilitations or reconstructions. The drawback of microsurfacing is its dependence on warm and dry weather. OPSS 336 states that microsurfacing can be applied when the following conditions are met: temperature of at least 10°C, no fog or rain, no forecast of temperatures below 0°C within 24 hours of application and between the dates of May 15th and September 30th [OPSS 336, 2009].

2.4.5. Diamond Grinding

Diamond grinding is a pavement preservation treatment used on rigid pavements to restore functional properties. The process involves the removal of a 4 to 8 mm of the surface layer using diamond saw blades; closely spaced grooves are produced. Surface irregularities caused by repeated traffic, joint faulting or faulty construction are removed in the process increasing pavement ride quality. This property has also been proven to reduce the traffic noise generated by the pavement. A rigid pavement can typically undergo three to four diamond grinding processes without fatiguing assuming the pavement is still structurally sound and has no visible signs of joint problems. The expected service life of diamond grinding is 10 years [Chan, 2010].

The major benefit of diamond grinding is the speed of implementation; work can be completed during the off peak hours. Other benefits include: cost effectiveness, reduced splash and spray, reduced hydroplaning, reduced user costs, adjusted cross slope, reduced noise level, improved ride comfort and increased skid resistance [Feldman, 2009].

2.4.6. Precast Concrete Panels

Precast concrete slab repair is an innovative pavement rehabilitation technique where deteriorated concrete sections are replaced by precast concrete slabs. In 2004, the Ministry of Transportation Ontario carried out a precast concrete slab repair pilot project on Highway 427 in Toronto. The project evaluated three methods repair methods which were: Fort Miller Super Slab™ Intermitted Method, Fort Miller Super Slab™ Continuous Method and the Michigan Method. The difference lies in the method used to install the concrete slabs and how the base is prepared. The installation process went well considering this was Canada's first experience with precast concrete slabs; the slabs did not rock, crack or spall. The only issue was workmanship which can be associated to a contractor carrying out precast concrete slab repair for the first time and under difficult conditions; night time construction, cold wet weather and a 6 hour construction window [Lane, 2007].

"Precast prestressed concrete pavement (PPCP) applications on pavement repair and rehabilitation projects throughout the United States during the last ten years have firmly established its ability to deliver important aspects of sustainability" [Merrit, 2011]. The PPCP concept was first introduced in 1998 when the Unites States Federal Highway Administration conducted a feasibility study to determine the concepts viability. Since then projects around the United States have implanted the practice to high degrees of success.

PPCP offers benefits in all three aspects of sustainability, economic, environmental and social. The primary benefit of precast concrete pavement is the speed the pavement can be installed and opened to the public. Precast concrete panels are produced and fully cured offsite allowing traffic to resume almost immediately after installation. This benefit allows construction to occur during short off peak hours or during the night time, which minimizes traffic disruption and the inconvenience experienced by the public. In addition to social benefits, minimized congestion results in environmental benefits as well. Minimized fuel consumption and air pollution due to idling are a few environmental benefit examples of PPCP [Merrit, 2011]. Benefits are also recognized through the materials used to produce the precast panels and the PPCP durability. Plant produced precast panels are steam cured which allows concrete mixtures to contain less concrete and more recycled materials such as fly ash and blast furnace slag. The precast concrete panel high material quality and production process ensures a durable product. PPCP requires little to no maintenance which minimizes pavement life cycle costs. Reduced maintenance also leads to the minimization of environmental and social impacts associated with maintenance activities. Prestressing concrete allows for a reduction in the pavement slab thickness which reduces material consumption up to 42% [Merrit, 2011]. The environmental impacts of plant to jobsite transportation are minimized by the thinner and lighter precast panels.

The US FWHA has completed six PPCP projects to date. The first project constructed a section of Highway 35 near Georgetown, Texas. This project demonstrated the material savings associated with PPCP by reducing the otherwise 355 mm thick cast-in-place pavement to a 200 mm thick PPCP. The success of the Highway 35 PPCP project has lead to future projects including two overnight projects where traffic was reopened the following morning [Merrit, 2011].

OPSS 363 provides the construction specifications for repairing rigid pavements with precast concrete slabs [OPSS 363, 2008].

2.4.7. Concrete Rubblization

Concrete rubblization is a pavement rehabilitation technique where the specialized equipment is used to break up the existing pavement surface; essentially transforming the existing pavement into a high quality aggregate base. OPSS 361 states that the broken concrete fragments must be less than 150 mm in the largest dimension [OPSS 361, 2005]. A thick bituminous layer is then placed on top of the rubblized concrete. The problem with the traditional concrete overlay technique is the reflective cracking occurring over underlying cracks and joints; concrete rubblization aims to overcome this limitation. Another benefit of concrete rubblization is the large amount of granular material savings resulting from the reuse of the existing pavement. This reduction in required material has both economic and environmental savings. However, the major drawback of concrete rubblization is the unknown subgrade conditions during the project design phase [Chan, 2010].

In 2006 the Illinois Department of Transportation released a paper outlining the results of their concrete rubblization performance evaluation study. The study evaluated 12 different projects where concrete rubblization was utilized; these 12 sites contained both interstate and non-interstate routes. The report states that "all rubblization projects constructed in Illinois have performed as well as, or better than, the control sections" [Wienrank, 2006]. The study found that rubblization is most viable when patching quantities exceed 10-15% of the existing pavement area. Additional consideration should be given to the location pipelines, utilities, surrounding buildings and overhead clearances [Wienrank, 2006].

2.4.8. Solar Heat-Blocking Pavement

Asphalt pavements have been integral in supporting economic and social activities and in the development of transport infrastructure. However with the continued rise of global warming, recent summers in Japan have set new records with asphalt surfaces reaching up to 60 ˚C. Asphalt pavements cover approximately 20% of the surfaces in urban centres leading to the phenomenon known as the urban heat island effect. These factors lead to an increased number of heatstroke patients. Increase asphalt pavement surface temperatures also lead to an increased rate of deterioration due to rutting, aging and fatigue. When combined, these factors warrant the need for preventative maintenance.

The Japanese have recently developed a maintenance technology which combats the rise of asphalt pavement temperatures. The technology involves the application of a coating material to the asphalt surface which increases the pavements solar reflectivity; pavements coated with the treatment material are called 'Solar Heat-blocking Pavements' [Masahiko, 2010]. The basic function of the coating is to reflect incoming solar rays which would normally be absorbed by the pavement therefore increasing the surface temperature. The coating is a paint based material consisting of three ingredients which are, resin, highly reflective pigment and hollow ceramic particles. The latter two ingredients are responsible for lower the pavement temperature; resin (Methyl Methacrylate) is added to allow the surface treatment to be applicable to porous pavements. The hollow ceramic particles have recursive reflection properties which allow solar rays to be reflected back along their incoming path [Masahiko, 2010]. This property prevents the rays from being reflected at and absorbed by adjacent buildings which would not reduce the urban heat island effect. The coating is approximately 1.0 mm thick and consists of three layers: prime layer, second layer and non-skid layer. The primary layer is applied first which is sprayed with non-skid sand to maintain surface friction; finally the second layer is applied to cover the non-skid sand. The coating must cure for an hour before traffic can be reopened [Masahiko, 2010].

A field test was conducted in Tokyo in 2004 where the performance of solar heat-blocking pavement was compared with conventional pavement. The maximum solar heat-blocking pavement surface temperature was measured at 42˚C, while the conventional pavement surface reached a maximum of 58˚C. The effect the coating has on porous pavements was also field tested. The test found that the applied surface treatment had no effect on the pavements permeability, surface friction or noise dampening properties. The long term durability effects of the surface treatment were tested on a taxiway at an international airport. The test compared the rut depths of the surface treated pavement to that of dense graded pavement after a four year period. The surface treatment was observed to reduce maximum rut depths by up to 50%. The major limitation of solar heat-blocking pavements is the cost; surfacing construction costs are comparable to that of dense-graded pavements [Masahiko, 2010].

2.5. Carbon footprinting

The carbon footprint of a project is defined as the total amount of greenhouse gases (GHG) emitted throughout all project phases; from conception to decommission. Several types of gases are considered GHG; however carbon footprinting is often expressed as the amount of CO_2 equivalent. Minimizing the carbon footprint of a project is a significant component of sustainability. “Combating the effects of climate change by mitigating GHG emissions and implementing adaptive measures is of paramount concern to the global community” [Monkman, 2010]. In response, significant efforts have been made to reduce the CO_2 emissions of the transportation industry. This section explores some of the advancements made towards minimizing the transportation industries carbon footprint.

2.5.1. Carbonation Curing

Current research shows that carbonation curing can be a sustainable alternative to steam curing of precast concrete. This process exposes “fresh precast concrete to carbon dioxide gas which then reacts to form thermodynamically stable carbonate microstructures” [Monkman, 2010]. In effect, instead of releasing CO_2 into the atmosphere (as per traditional steam curing), CO_2 is consumed. The potential benefits of carbonation curing include minimized unit production costs, equivalent or improved performance and reduced GHG emission. Lab tests show carbonation cured precast concrete has similar or superior material properties to steam cured precast concrete in terms of, early strength, late strength, freeze/thaw resistance, water absorption and pH. A pilot project has been undertaken by Carbon Sense Solutions Inc to “demonstrate the industrial application of this process, identify optimal operating conditions, validate the CO_2 mitigation potential and investigate the material property performance of carbonated products” [Monkman, 2010].

While the primary environmental incentive of carbonation curing is the GHG mitigation potential, reductions in water consumption, cement requirements and NO_x and SO_x emissions are also achieved. Carbonation curing reduces CO_s emissions in two ways; a fuel consumption reduction during manufacturing and through the carbonation of calcium silicate and hydroxide minerals found in cement. The process will reduce CO_2 emissions by approximately 120kg/t concrete. Widespread implementation of carbonation curing is estimated to reduce CO_2 emissions by several million tonnes per year [Monkman, 2010].

The primary economic incentive of carbonation curing is the reduced operating costs achieved through lower energy (44%) and water (39%) consumption. Carbonation curing can be employed through a low cost retrofit of existing plant equipment. Additional economic incentives are accomplished through faster production, less inventory handling and potential carbon tax relief. Finally, additional bids may be won since consumers and building codes are gradually demanding environmentally friendly products [Monkman, 2010].

Global warming is one of the greatest threats affecting today's society. The principal social benefit of carbonation curing is the minimization of the cement industry's effect on global warming. Studies have shown that carbonation curing has the potential to reduce the cement industries carbon footprint by approximately 21% of their 2007 emission [Monkman, 2010].

2.5.2. Supplementary Cementing Materials

Utilizing supplementary cementing materials (SCM) can significantly reduce the carbon footprint of the concrete industry. The general rule of thumb is that 1 tonne of CO_2 is released for every tonne of Portland cement (clinker) produced. Therefore reducing the demand for clinker is one approach for minimizing the carbon footprint of the cement industry. Clinker consumption can be reduced by producing blended cements consisting of Portland cement and a SCM. Another approach is to produce Portland limestone cements (PLC); by definition these cements contain more than 5% limestone.

A recent study in Nova Scotia examined the performance of concrete produced with blended Portland cement containing slag and concrete produced with PLC. The study tested the performance of blended portland limestone cement with 15% slag and 12% limestone (type GULb), and blended portland cement containing 15% slag (type GUb) with traditional portland cement (type GU). Lab tests indicated that both test cements produced similar performance levels to type GU cement. The following lab tests were completed: compressive test, rapid chloride permeability test and Deicer salt scaling test. Type GULb and GUb cements contain approximately 27% and 15% less clinker than type GU, respectively. These blended cements would significantly reduce the CO_2 associated with finished cement. For example, a plant which produces 300,000 tonnes of cement annually, switches from type GU cement to type GULb. This switch would reduce the CO_2 emissions of that plant by approximately 70,000 tonnes per year [Thomas, 2010].

Flash metakaolin is a supplementary cementing material utilized in precast concrete applications. A recent study was conducted where different proportions of flash metakaolin were tested based on mechanical and durability properties. Cement 1 (C1) was composed of traditional cement while cement 2 (C2) replaced 18% of the clinker by weight with blast furnace slag. The flash metakaolin content within the C1 and C2 mixes were incrementally increased (0%, 12.5% and 25%). The objective of this study was to quantify the mechanical (flexural and compressive strength) and durability properties (permeability and water absorption) of cements containing flash metakaolin. The results showed that substituting 25% of cement with flash metakaolin has little effect on the 1 day flexural strength of the concrete but increases the 28 day strength. With respect to compressive strength, while C1 performed poorly with flash metakaolin. However, both the 1 day and 28 day compressive strengths of C2 was significantly improved with flash metakaolin. Performance was maintained from a durability perspective; permeability and water absorption were largely unaffected by the incorporation of flash metakaolin. From an environmental point of view, reducing clinker consumption helps minimize energy consumption and helps control the carbon footprint by reducing CO_2 emissions.

2.5.3. ECOAGE, Quantifying Greenhouse Gas Emissions

The company AMEC has recently developed a software entitled Environmental Comparison of Aggregate/asphalt Greenhouse gas Emissions (ECOAGE) which is a software program that can assess greenhouse gas reductions accrued by utilizing road recycling processes when compared to traditional maintenance strategies [Holt, 2010]. The program is designed to estimate greenhouse gas production quantities in terms of CO_2 equivalence for different maintenance alternatives. These evaluations can be conducted on both project-by-project basis or over the project life cycle [Holt, 2010].

Emissions under ECOAGE are calculated under three different phases which are material production/processing, material transportation and material placement. Material production/processing considers the emissions generated during the production of non-renewable resources such as extractment and refinement of bituminous products. Material transportation considers the emissions produced during the transportation of these non-renewable resources. Material placement considers the emissions generated as a result on-site material placement. ECOAGE calculates the CO, CO_2, NO_x, SO_x, and PM_{10} emissions at each of the three phases [Holt, 2010].

The province of Nova Scotia has been utilizing road recycling technologies and techniques since 2002. In order to demonstrate the environmental benefit of Nova Scotia's recycling activities, a highway section maintained using recycling processes was analysed using ECOAGE. Table 2.4 displays the results obtained from the ECOAGE analysis. CO_2 emissions were reduced by 387,035 kg which is approximately 30%. The majority of the CO_2 reductions occurred during the material production/processing and material transportation phases. Since material is being recycled, less virgin material is required resulting in lower extraction and processing emissions. In addition, fewer trucks are required for material transportation resulting in lower transportation emissions. Material placement emissions were relatively equal under two strategies [Holt, 2010].

Table 2.4 – ECOAGE Emissions Results [Holt, 2010]

Strategy	Emissions (kg)				
	CO_2	CO	NO_x	SO_x	PM_{10}
Recycling	919291	1750	3176.5	4891.1	4350.6
Traditional	1306326	2475	3845.1	6211.3	8508.6
Reduction	29.6%	29.3%	17.4%	21.3%	48.9%

2.5.4. Life-Cycle Assessments

A life cycle assessment (LCA) is a method used to quantify the environmental impacts of products or services, including pavements. It was first introduced to the road sector in the mid-1990s and has since been gaining popularity. A recent study by the Massachusetts Institute of Technology and the University of California conducted a critical review of pavement LCA. The study points out that “inconsistencies in the functional unit, system boundaries, data qualities and environmental metrics have created a situation where different studies are largely incompatible and incomparable” [Santero, 2010]. These inconsistencies threaten to undermine the fundamental purpose of LCAs, which is to provide decision makers with an additional tool for determining the total impacts of projects and policies. The study raises attention to the areas of the pavement LCA framework that are incomplete or ineffectively incorporated. These areas are, traffic delay, rolling resistance, concrete carbonation, pavement albedo, lighting, leachate and end of life allocation. “These components produce quantitative gaps in the assessment methodology, thus jeopardizing the accuracy of results and defensibility of conclusions” [Santero, 2010]. Life cycle assessments have the potential to greatly aid decision makers; however the process requires significant resources and still requires fine tuning. To undertake research in the gaps identified above, robust data support from ideally developed tools is required.

2.6. Sustainability Evaluation Tools

As the concept of sustainable pavements continues to spread, the need for agencies to quantify the sustainability benefits of various practices will continue to grow. In response, these agencies will develop different tools which will allow them to quantify pavement sustainability. A few of the more prominent tools developed are evaluated within this section; these tools are LEED®, GreenLITES, Greenroads, GreenPave, Sustainable Highways Self-Evaluation Tool and Envision. The quantification of pavement sustainability is a relatively new topic therefore it is important to note that a few of these rating systems are still under development.

2.6.1. LEED®

Leadership in Energy and Environmental Design (LEED®) was initially developed by the United States Green Buildings Council (USGBC). Their Canadian counterpart, Canada Green Buildings Council (CaGBC), aims to “lead and accelerate the transformation to high-performing, healthy green buildings, homes and communities throughout Canada” [CaGBC, 2011]. The CaGBC received permission to adapt LEED® to Canadian practices and regulations in 2003 and hence developed the LEED® Green Building Rating System. This rating system was defined by the CaGBC as a system which “encourages and accelerates global adoption of sustainable green building and development practices through the creation and implementation of universally understood and accepted tools and performance criteria” [CaGBC, 2011].

LEED® is an internationally recognized third party certification program for the design, construction and operation and maintenance of green buildings. Projects must be registered and processed by the CaGBC for a fee before certification is granted. Each project is evaluated based on six categories which are [CaGBC, 2011]:

- Sustainable Site Development
- Water Efficiency
- Energy Efficiency
- Materials Selection
- Indoor Environmental Quality
- Innovation

The sixth category "innovation" allows techniques or technologies previously not included within the LEED® rating system to receive credits. This is a major strength of the LEED® rating system since it allows the program to continually grow and meet the advances in techniques and technologies. These categories are further divided into credits which are used to evaluate projects in question. If a project meets a certain credit it receives points. These points are summed into a grand total for the project once it has been evaluated by all credits. There are a total of 100 credits available plus 6 for an innovative design. LEED® has four different certification levels which are certified, silver, gold and platinum; each level of certification being progressively more difficult to achieve. The required points for each certification level are as follows:

- Certified 40 - 49 points
- Silver Certified 50 - 59 points
- Gold Certified 60 - 79 points
- Platinum Certified 80+ points

LEED® certification mainly focuses on the evaluation of buildings and has little applicability to sustainable pavement practices. However, LEED® is a perfect role model for any developed and under-development pavement sustainability evaluation systems.

2.6.2. GreenLITES

The GreenLITES (Leadership In Transportation and Environmental Sustainability) is a transportation sustainability rating system developed by the New York State Department of Transportation (NYSDOT) for the purposes of evaluating their internal design projects in terms of sustainability. GreenLITES evaluates all aspects of transportation including pavements, traffic, materials, water quality and lighting. NYSDOT developed GreenLITES to better integrate the following concepts into their design philosophy [NYSDOT, 2008]:

- Protect and enhance the environment
- Conserve energy and natural resources
- Preserve or enhance the historic, scenic, and aesthetic project setting characteristics
- Encourage public involvement in the transportation planning process
- Integrate smart growth and other sound land-use practices
- Encourage new and innovative approaches to sustainable design

"GreenLITES is a self-certification program which distinguishes transportation projects based on the extent to which they incorporate sustainable design choices" [NYSDOT, 2008]. Projects are evaluated based on sustainability and can be granted various levels of certification based on the total number of points. GreenLITES credits are organized into categories which are [NYSDOT, 2008]:

- Sustainable Sites
- Water Quality
- Material and Resources
- Energy and Atmosphere
- Innovation /Unlisted

The GreenLITES score card is extensive and contains over 200 possible points. However, since GreenLITES evaluates all aspects of transportation, each individual project is only evaluated based on relevant credits therefore the maximum achievable point score is much lower.

The different achievement levels under the GreenLITES system are non-certified, certified, silver, gold and evergreen; each achievement level is progressively more difficult to achieve than the last. To establish the achievement level requirements, the NYSDOT evaluated a large variety of projects using GreenLITES. Based on their results, projects within the bottom third of total points earned received no certification; projects within the middle third received basic certification and projects within the top third were further divided into three achievement levels. Projects between the 67th and 90th percentile received silver certification, projects between the 90st and 98th percentile received gold certification and projects within the top two percent received evergreen certification. Table 2.5 displays the GreenLITES achievement level point ranges [NYSDOT, 2008].

Table 2.5 – GreenLITES Certification Levels [NYSDOT, 2008]

Name	Point Range	Percentile Range
Non-certified	0 – 14	< 33%
Certified	15 – 29	33 – 67%
Silver	30 – 44	67 – 90%
Gold	45 – 59	90 – 98%
Evergreen	60 & up	> 98%

Table 2.6 demonstrates the GreenLITES scorecard format. Each credit has an associated description and an available point score. If a project meets the credit criteria it is awarded the total available points. However, if it does not meet the credit criteria, the project is not awarded points. For example: under credit S-1a, if a project design avoids previously undeveloped lands it is awarded 2 points, if it does not 0 points are awarded. A project cannot receive 1 point for partially avoiding undeveloped lands.

2.6.3. Greenroads

Greenroads is a rating system used to evaluate a projects design and construction in terms of sustainability. The Greenroads concept was initially begun by Soderlund and Muench, at the University of Washington in 2007. The original thesis entitled "Sustainable Roadway Design: a Model of an Environmental Rating System" was continued by a joint effort between the University of Washington and CH2M Hill Inc. and resulted in today's Greenroads program. Similar to LEED®, Greenroads is a third party certification system. Therefore applicable fees and project documentation must be submitted to, reviewed and evaluated by Greenroads before certification is granted. A Greenroad is defined as a "roadway project that has been designed and constructed to a level of sustainability that is substantially higher than current common practice" [Greenroads, 2011].

Table 2.6 – GreenLITES Scorecard [NYSDOT, 2008]

GreenLITES Project Environmental Sustainability Rating System Scorecard					
CATEGORY		ID	DESCRIPTION	POINTS	
				Available	Scored
Sustainable Sites (S)	S-1 *Alignment Selection*	S-1a	Avoidance of previously undeveloped lands (open spaces or greenfields).	2	
		S-1b	Alignment establishes 100' buffer between highway & natural watercourse/wetland.	2	
		S-1c	Alignment which minimizes overall construction "footprint" to avoid or minimize the introduction of new areas requiring mowing.	2	
		S-1d	Minimize total earthwork by matching proposed vertical alignments as closely as possible to existing grades.	1	
	S-2 *Context Sensitive Solutions*	S-2a	Adjust highway features to respond to the area's unique character.	2	
		S-2b	Incorporate local or natural materials for substantial visual elements.	2	
		S-2c	Visual enhancements (screen objectionable views, enhance scenic views).	2	
		S-2d	Period street furniture/lighting/appurtenances.	1	
	S-3 *Land Use/ Community Planning*	S-3a	Use of more engaging public participation techniques (charette, task force, etc).	2	
		S-3b	Enhanced outreach efforts (e.g. newsletters, project-specific Web page).	2	
		S-3c	Projects promoting use of public transit (e.g. "Park-and-Ride").	2	
		S-3d	Project applies "Walkable Communities"/"Complete Streets" concepts.	2	

Greenroads is a collection of sustainability best practices with respect to the design and construction of roadways. These best practices are divided into two types, required and voluntary. There are a total of 11 required credits, all of which must be met in order for a project to be considered for certification. These project requirements cover the most significant sustainability principles of any roadway project throughout the entire life cycle. Voluntary credits are best practices which are not necessarily required for certification but if met, will positively contribute to Greenroads decision to award certification. Each voluntary credit is weighted between 1-5 points based on its impact on sustainability. There are a total of 37 voluntary credits grouped into the following categories [Greenroads, 2011]:

- Environment and Water — 21 Points
- Access and Equity — 30 Points
- Construction Activities — 14 Points
- Materials and Resources — 23 Points
- Pavement Technologies — 20 Points
- Custom Credits — 10 Points

Total — 118 Points

The custom credits category is similar to the Innovation category observed in the LEED® and GreenLITES rating systems. This category allows credit to be given to sustainable practices and technologies currently not included within Greenroads. The two categories related to pavement engineering are Materials and Resources (MR) and Pavement Technologies (PT). Table 2.7 displays a screen capture of the Greenroads scorecard outlining 11 project requirements and the MR and PT voluntary credits.

Table 2.7 – Greenroads scorecard [Greenroads, 2011]

GREENROADS RATING SYSTEM

LIST OF CREDITS (v1.5)

No.	Title	Pts.	Description
Project Requirements (PR) – Mandatory for all projects			
PR-1	Environmental Review Process	Req	Complete a comprehensive environmental review
PR-2	Lifecycle Cost Analysis (LCCA)	Req	Perform LCCA for pavement section
PR-3	Lifecycle Inventory (LCI)	Req	Perform LCI of pavement section
PR-4	Quality Control Plan	Req	Have a formal contractor quality control plan
PR-5	Noise Mitigation Plan	Req	Have a construction noise mitigation plan
PR-6	Waste Management Plan	Req	Have a plan to divert C&D waste from landfill
PR-7	Pollution Prevention Plan	Req	Have a TESC/SWPPP
PR-8	Low Impact Development (LID)	Req	Complete a LID feasibility study
PR-9	Pavement Management System	Req	Have a pavement management system
PR-10	Site Maintenance Plan	Req	Have a roadside maintenance plan
PR-11	Educational Outreach	Req	Publicize sustainability information for project
Materials & Resources (MR) – Up to 23 Points			
MR-1	Life Cycle Assessment (LCA)	2	Conduct a detailed LCA of the entire project
MR-2	Pavement Reuse	1-5	Reuse existing pavement sections
MR-3	Earthwork Balance	1	Use native soil rather than import fill
MR-4	Recycled Materials	1-5	Use recycled materials for new pavement
MR-5	Regional Materials	1-5	Use regional materials to reduce transportation
MR-6	Energy Efficiency	1-5	Improve energy efficiency of operational systems
Pavement Technologies (PT) – Up to 20 Points			
PT-1	Long-Life Pavement	5	Design pavements for long-life
PT-2	Permeable Pavement	3	Use permeable pavement as a LID technique
PT-3	Warm Mix Asphalt (WMA)	3	Use WMA in place of HMA
PT-4	Cool Pavement	5	Contribute less to urban heat island effect (UHI)
PT-5	Quiet Pavement	2-3	Use a quiet pavement to reduce noise
PT-6	Pavement Performance Tracking	1	Relate construction to performance data

Four different certification levels may be achieved by projects under the Greenroads rating system. These four certification levels are certified, silver, gold and evergreen. Table 2.8 displays the requirements needed for projects to achieve the different certification levels. As previously mentioned, all 11 project requirements must be met for certificate consideration.

Table 2.8 – Greenroads Certification Levels [Greenroads, 2011]

Certification Level	Requirements
Certified	11 Project Requirements and 32 - 42 voluntary credits
Silver	11 Project Requirements and 43 - 53 voluntary credits
Gold	11 Project Requirements and 54 - 63 voluntary credits
Evergreen	11 Project Requirements and 64+ voluntary credits

2.6.4. GreenPave

GreenPave is defined as a "simple points based rating system designed to assess the "greenness" of pavement" [Lane, 2011]. The main objective of GreenPave is to provide a rating system for assessing the sustainability of pavement design and construction projects. GreenPave is based on GreenLITES, Greenroads and LEED® but is customized for Ontario climates, standards and legislations. The main difference between GreenPave and competing systems is that GreenPave focuses specifically on pavement projects instead of the entire road; GreenPave is applicable to both flexible and rigid pavements. GreenPave is currently under-development by the Ontario Ministry of Transportation therefore the presented credits and credit weightings are subject to change. There are four categories within the GreenPave program which, along with their point totals and objectives are displayed in Table 2.9.

Table 2.9 – GreenPave Category Overview [Lane, 2011]

Category	Goal	Points
Pavement Technologies	Optimization of sustainable design.	9
Materials and Resources	Optimization of usage/reusage of recycled materials and minimization of material transport distances.	11
Energy and Atmosphere	Minimization of greenhouse gas emission and energy consumption.	8
Innovation and Design Process	Recognition of sustainable technologies and techniques currently not included within GreenPave.	4

Each category is further divided into subcategory credits; Figure 2.1 displays an overview of the GreenPave categories and subcategories and the points associated with each criterion. Similar to Greenroads and GreenLITES, GreenPave also contains an Innovations category which allows unaccounted sustainable technologies and techniques to receive points.

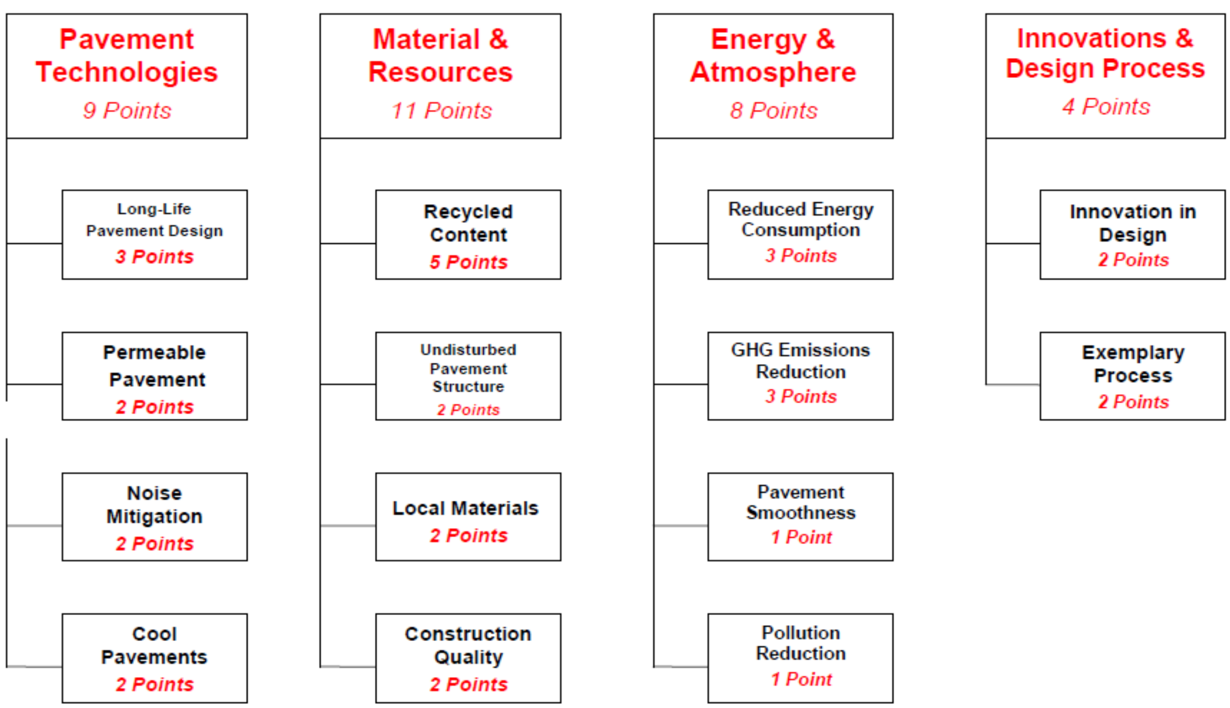


Figure 2.1 – GreenPave Scorecard Overview [Lane, 2011]

There is a total of 32 points available under the GreenPave point system. Project may be awarded points between 0 and the specified maximum based on the degree at which credit objectives are met. Figure 2.2 illustrates a sample scorecard from the GreenPave system; the credits objective, applicability and point ranges are displayed. Under the MR-2 credit, the maximum points a project can achieve is 3. For example: a rehabilitation project would receive 2 out of 3 points if 80% of the existing pavement was maintained.

GreenPave developers propose achievement levels similar to the GreenLITES system. The GreenPave achievement levels and their corresponding point ranges are as follows:

- Non-Certified — 0 – 9 points
- Bronze Certified — 10 – 14 points
- Silver Certified — 15 – 19 points
- Gold Certified — >=20 points
- Trillium Certified — Future development

The displayed point ranges are subject to change since GreenPave is currently under-development.

MR-2: Reuse of Pavement (3 Points)

Objective:

To encourage reusing existing pavement materials in the new pavement structure.

Applicability:

To rehabilitation projects that leave a portion of the pavement structure undisturbed and new construction projects that make use of cut material as fill material within the right of way.

Points:

	Rehabilitation Projects
	• Maintain at least 50% of the existing pavement.
	• Maintain at least 70% of the existing pavement.
	• Maintain at least 90% of the existing pavement.

	New Construction Projects
	• At least 50% of the cut material is reused in the right of way.
	• At least 70% of the cut material is reused in the right of way.
	• At least 90% of the cut material is reused in the right of way.

Figure 2.2 – GreenPave Sample Scorecard [Lane, 2011]

2.6.5. Sustainable Highways Self-Evaluation Tool

The Sustainable Highways Self-Evaluation tool is a self-certification online tool which assists organizations in incorporating sustainable best practices into their roadway projects and programs. This self-evaluation tool is currently being developed by the United States Department of Transportation, Federal Highway Administration; therefore information presented within this report is subject to change. The main objective is to “encourage more sustainable practices in roadway planning, design, construction and operations and maintenance” and to “provide a standard quantitative means of roadway sustainability assessment” [US DOT, 2010].

The Sustainable Highways Self-Evaluation tool is a collect of sustainability best practices called credits. These credits have a certain number of points assigned to them representing their relative impacts on roadway sustainability. A project, program or system is evaluate based on all credits and the achieved points are added together to give a total score.

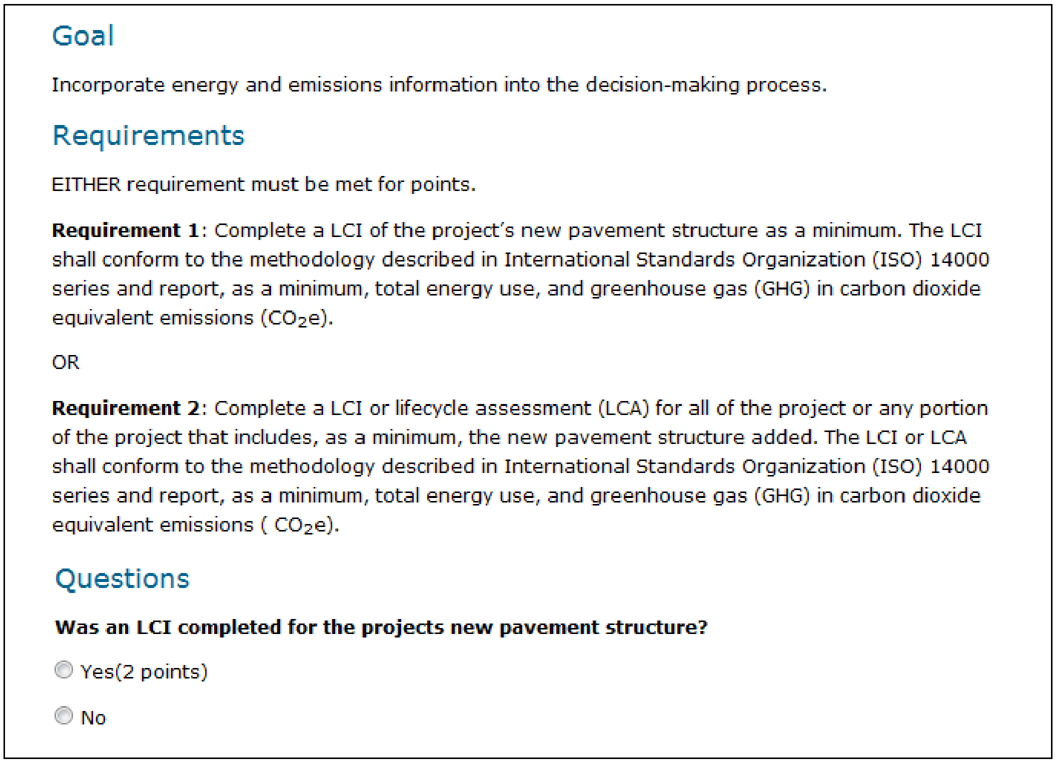
Credits are organized into three different categories which are System Planning (SP), Project Development (PD) and Operations and Maintenance (OM). System planning credits evaluate the organization wide management and planning of road networks; they evaluate an organizations procedures, policies and systems and not individual projects. In other words, SP evaluates an organizations network level sustainability. Project Development credits are designed to evaluate individual projects throughout its entire life cycle (environmental assessment, project planning, design, construction and operations and maintenance). Like System Planning, Operations and Maintenance credits evaluate an organizations network level. “These credits are concerned with agency-wide practices, policies and procedures required for the overall functionality and efficiency of a highway network” [US DOT, 2010]. Each category is a standalone evaluation tool.

There are four different achievement levels available under the Sustainable Highways tool. A project, program, policy or system must achieve 30%, 40%, 50% or 60% of the total points to achieve bronze, silver, gold or platinum certification respectively. For example: a program being evaluated under the SP category must achieve between 56 and 69 points to receive silver certification. Table 2.10 displays the point requirements of each achievement level in each category.

Table 2.10 – Sustainable Highways Self-Evaluation Tool Category Overview [US DOT, 2010]

	System Planning	Project Development	Operations & Maintenance
Total Points	140	124	150
BRONZE (30%)	42	37	45
SILVER (40%)	56	50	60
GOLD (50%)	70	62	75
PLATINUM (60%)	84	74	90

Individual credits not applicable to the program, policy or project in question may be excluded from the evaluation. Figure 2.3 displays a sample credit scorecard of the Sustainable Highways tool. The goal of the credit is described as well as the credit requirements. The user answers the question based on the described requirements and the item being evaluated is either awarded the points or not. The point score associated with the credit in question is displayed.



Goal

Incorporate energy and emissions information into the decision-making process.

Requirements

EITHER requirement must be met for points.

Requirement 1: Complete a LCI of the project's new pavement structure as a minimum. The LCI shall conform to the methodology described in International Standards Organization (ISO) 14000 series and report, as a minimum, total energy use, and greenhouse gas (GHG) in carbon dioxide equivalent emissions (CO_2e).

OR

Requirement 2: Complete a LCI or lifecycle assessment (LCA) for all of the project or any portion of the project that includes, as a minimum, the new pavement structure added. The LCI or LCA shall conform to the methodology described in International Standards Organization (ISO) 14000 series and report, as a minimum, total energy use, and greenhouse gas (GHG) in carbon dioxide equivalent emissions (CO_2e).

Questions

Was an LCI completed for the projects new pavement structure?

- Yes(2 points)
- No

Figure 2.3 – Sustainable Highways Self-Evaluation Tools Sample Scorecard [US DOT 2010]

2.6.6. Envision

The Envision (ISI) Sustainability Rating System contains a set of objective based goals which will guide decision makers towards making sustainable choices. The ISI rating system can be applied to all fields of infrastructure including roads, bridges, transit systems, water and wastewater systems, energy generation and transmission and other physical facilities. Work on ISI officially began in February 2011 by a group comprised of members from the American Council of Engineering Companies (ACEC), American Public Works Association (APWA) and American Society of Civil Engineers (ASCE) [Envision, 2011].

Envision is currently under development, therefore any details provided within this report is subject to change. Currently ISI consists of 10 primary criteria and 74 sub criteria. The criteria cover all phases of a project from conceptual and planning to project management and delivery; all three aspects of the sustainability triple bottom line are covered. ISI consists of a series of modules covering all fields of infrastructure; modules unrelated to a project may be disregarded. This allows practitioners to customize ISI to suit the needs of their particular application [Envision, 2011].

Envision will provide practitioners with four levels of application. Interested users will be granted access to these resources online allowing them to use the material for guidance and self-assessment. The second level will allow parties to hire ISI certified Assessors who are trained in the rating system use. These Assessors will guide interested parties to more sustainable solutions and can apply to ISI for formal project recognition. The third level is a third party verification stage; formal project evaluation will be conducted by ISI who may grant infrastructure projects excelling in sustainability formal recognition. Award recognition is scheduled to begin in early to mid-2012. The fourth level is Envisions' software for alternative solutions and costing; this software is planned for the future [Envision, 2011].

2.7. Chapter 2 Summary

This literature review identifies and reviews the state-of-the-art pavement sustainability best practices. These practices are divided into five categories which are materials, designs and construction techniques, maintenance and rehabilitation techniques, carbon foot printing and sustainability evaluation tools. Table 2.1 displays all evaluated technologies.

In terms of materials, the City of Markham currently utilizes RAP and RAS, the next step would be to experiment with higher percentages of RAP and recycled crumb rubber. In terms of construction techniques, Markham favours conventional asphalt pavement with varying percentages of RAP. However, pervious pavements are being considered as viable alternatives in select locations. Markham currently does not evaluate construction and rehabilitation projects in terms of sustainability. Chapter 4 of this document provides a detailed examination of GreenPave and explores the possibility of applying it to City of Markham pavement projects.

Through the completion of the literature review it is concluded that there is a wide variety of sustainable pavement technologies that range from project design to pavement decommission. Chapter 3 analyses the environmental, economical and carbon footprint impacts of twelve pavement best practices identified within the literature review.

Chapter 3
QUANTIFYING TYPICAL SAVINGS

3.1. Introduction

The objective of this chapter is to assess and evaluate the expected savings when utilizing the different sustainable pavement engineering practices discussed in the literature review. This evaluation is broken down into four categories: economic, environmental, social and carbon footprinting. The research team collaborated with the City of Markham in collecting field data on the typical savings of various technologies including, RAP, CIP and CIREAM. Additional analysis and research was required on: RCA, RAS, warm asphalt and pervious/porous pavement technologies as the City was not currently working with these technologies. The goal of chapter 3 is to determine the performance differences between various pavement engineering techniques.

3.2. Environmental Savings Using Palate

3.2.1. PaLATE Introduction

For the purposes of this project, the environmental savings quantification was completed using the Pavement Life-cycle Assessment Tool for Environmental and Economic Effects (PaLATE) [Horvath, 2007]. Appendix A provides a walkthrough of PaLATE providing new users an opportunity to become familiar with the program. PaLATE was developed by a small team of researchers lead by Dr. Arpad Horvath at the University of California, Berkley. Dr. Horvath defines PaLATE as an "excel-based tool for life-cycle assessment (LCA) of environmental and economic effects of pavements and roads. The tool takes user input for the design, initial construction, maintenance, equipment use, and costs for a roadway, and provides outputs for the life-cycle environmental effects and costs" [Horvath, 2007]. PaLATE investigates the following environmental effects: energy consumption, water consumption and CO_2, CO, NO_x, PM_{10}, SO_2, Hg and Pb emissions. PaLATE also outputs the RCRA hazardous waste generation and cancerous and non-cancerous human toxicity potential [Horvath, 2007]. PaLATE was designed in the United States of America; therefore all units must be converted to the imperial system for PaLATE to be implemented by the City of Markham.

The pavement technologies evaluated using PaLATE are summarized in Table 3.1. The technologies have been evaluated using data provided from the City of Markham and other sources, namely from other published research, CPATT and other Canadian sources. In order to estimate the environmental impact of the listed technologies, PaLATE requires user input falling under three categories; pavement layer specifications, pavement material specifications and material transportation. PaLATE was developed in the United States therefore all units must be converted into the imperial system.

Table 3.1 – Evaluated Pavement Technologies

New Construction	Maintenance & Rehabilitation
Hot Mix Asphalt (Control)	Cold In-Place Recycling
Hot Mix Asphalt with 20% RAP	Cold In-Place Recycling with Expanded Asphalt Material
Hot Mix Asphalt with 3% RAS	Full Depth Reclamation
Porous Asphalt Local	Mill and Asphalt Overlay
Pervious Concrete	Mill and Asphalt Overlay with 20% RAP
Warm Mix Asphalt	Microsurfacing

3.2.2. PaLATE Input

The pavement layer specification worksheet describes the pavement dimensions (width, length and depth) of each layer from wearing course to subbase. City of Markham roads fall under five working classifications which are: industrial, laneway, local, major collector and minor collector. Pavement width and depth depend on the road classification while a control length of 1.0 km was adopted for this study. Table 3.2 displays the pavement dimensions of all five City of Markham road classifications [TOM, 2011]. In addition to pavement dimensions, this worksheet allows users to input material and process densities. The default values provided by PaLATE were used for the purposes of this project. Pavement designs for all analysed pavement technologies are presented in Appendix B.

Table 3.2 – Pavement Dimensions based on Road Classifications [TOM, 2011]

Category	Width (m)	Depth (mm)			
		Surface Course Asphalt	Base Course Asphalt	Granular A	Granular B
Industrial	13.0	50	100	150	450
Laneway	5.5	40	75	150	300
Local	8.5	40	75	150	300
Major Collector	13.0	50	100	150	450
Minor Collector	11.0	50	100	150	450

The second worksheet, pavement material specification, requires the user to input the material volumes used in each pavement layer. Two assumptions were made for simplification purposes. First, Hot Mix Asphalt (HMA) is assumed to contain 95% aggregates and 5% bitumen. Second, PaLATE is not programmed to analyse Warm Mix Asphalt (WMA), therefore WMAs environmental savings were determined by discounting a certain percent from the HMA emission results. These percentages were formulated through a literature review; detailed information presenting the results of this literature review are located in Appendix B.

The third component, material transportation, requires the user to input the transportation distance and mode for each material. The transportation distances and modes were provided by the City of Markham and are summarized in Table 3.3. All materials are obtained from the Miller Groups' yard except for virgin aggregate, granular A and granular B which are obtained from Uxbridge. The Miller yard is located within the heart of the City of Markham; therefore a transportation distance of 10 km was assumed for all Miller Yard materials. Dump trucks are used for all materials with the exception of bitumen and asphalt emulsion which are transported using tanker trucks. Detailed PaLATE documentation for all pavement technologies is located in Appendix B.

Table 3.3 – Material Transportation Distances and Modes

Item	Transportation Distance	Transportation Mode
Virgin Aggregate	38.2 km	Dump Truck
Bitumen	10 km	Tanker Truck
Asphalt Emulsion	10 km	Tanker Truck
RAP to Site	10 km	Dump Truck
RAP to Landfill	10 km	Dump Truck
Gravel to Site	38.2 km	Dump Truck
Rock to Site	38.2 km	Dump Truck

3.2.3. PaLATE Results

This section presents a summary of the PaLATE output; detailed numerical and graphical results are located in Appendix C. Six different initial construction technologies are evaluated using PaLATE which are: traditional Hot Mix Asphalt (HMA), HMA containing Reclaimed Asphalt Pavement (RAP), HMA containing Recycled Asphalt Shingles (RAS), porous asphalt pavement, pervious concrete pavement and warm asphalt pavement. Traditional HMA was adopted as the control technology to which all the other technologies are compared. These pavement technologies are evaluated using the following environmental impacts: energy consumption, water consumption and carbon dioxide, carbon monoxide, nitrous oxide, particulate matter 10, sulphur dioxide, mercury and lead emissions.

The conducted PaLATE analysis was grouped into five categories which are the five road classification; industrial, laneway, local, major collector and minor collector. Each pavement technology displayed in Table 3.1 was analysed under all five road classifications. All pavement designs were based on the specifications provided by the City of Markham [TOM, 2011] and are located in Appendix B. It should be noted that HMA containing RAP is designed identical to the control HMA except wearing courses 1 and 2 contain 15% and 20% RAP respectively replacing virgin aggregate. Past research indicates that asphalt shingles contain approximately 30-40% asphalt cement by weight; therefore 3% RAS contributes approximately 1% by weight of the required asphalt binder. The porous asphalt pavement design contains two major differences when compared to the HMA design. Wearing courses 1 and 2 contain 93% aggregate and 7% bitumen; more bitumen is required to hold the aggregates together because of the pores created by the absence of fine aggregates. The second difference lies in the base/subbase which is a single 450mm open drainage layer. The warm mix asphalt pavement design is identical to the control HMA design.

Pavement technologies tend to have different service lives; therefore comparing pavement technologies based on total emissions isn't valid. To compare these pavement technologies, the PaLATE results were converted into equivalent annual emissions. Service lives were obtained from the Transportation Association of Canada (TAC) Pavement Design and Management Guide [TAC, 2012]. Table 3.4 displays the expected service lives of the five evaluated initial construction pavement technologies. In this case, all technologies have an expected service life of 15 years except pervious concrete which has a service life of 20 years.

Table 3.4 – Initial Construction Expected Service Lives

Process	Life Span
HMA (Control)	15
HMA with RAP	15
HMA with RAS	15
Porous Asphalt	15
Pervious Concrete	20
Warm Mix Asphalt	15

Table 3.5 displays the PaLATE results of the five tested initial construction pavement technologies under the local road classification. Similar tables for all road classifications are located within Appendix C. The results indicate that Warm Mix Asphalt pavement is the most environmentally friendly option; resulting in significant savings in energy consumption and CO_2, CO, NO_x, and SO_2 emissions. Adding RAP to HMA reduces energy and water consumption and all emissions except for mercury; however, the increase in mercury emissions is negligible. Adding RAS to the mix design reduces emissions energy and water consumption and all emissions. Porous asphalt consumes less energy and water and emitts less harmful gases than pervious concrete; however, due to the longer life span of pervious concrete, it becomes the more environmentally friendly option. Both porous asphalt and pervious concrete are less environmentally friendly than the control in terms of construction. Similar observations can be made for the other four road classifications.

The pavement technique chosen as the control for rehabilitation is Mill and Overlay (M&O). This technique was chosen since it is the most common pavement rehabilitation technique. The M&O and all other rehabilitation technique designs are located within Appendix B. For comparison purposes, the PaLATE results for each rehabilitation technique were converted into equivalent annual emissions. Service lives were obtained from the (TAC) Pavement Design and Management Guide [TAC, 2012]. The Guide provided a range of expected service lives for each rehabilitation technique instead of a fixed number. Therefore, the average of each range was assumed to be the service life of the rehabilitation technique in question. Table 3.6 displays the expected service lives of all analyzed pavement rehabilitation techniques. Full depth reclamation has the longest expected service life while microsurfacing has the shortest.

Table 3.5 – Local Road Initial Construction PaLATE Results

Process	Energy [MJ]	Water Consumption [kg]	CO_2 [Mg] = GWP	NO_x [kg]	PM_{10} [kg]	SO_2 [kg]	CO [kg]	Hg [g]	Pb [g]
Total Emissions									
HMA (Control)	3128695	684	186	1962	1666	26818	496	2	126
HMA with RAP	3046840	672	181	1919	1581	26811	488	2	125
HMA with RAS	2913334	595	174	1892	1654	26494	446	2	109
Porous Asphalt	4189786	956	255	2463	2331	27055	672	3	176
Pervious Concrete	4452429	1328	314	3744	2659	1831	1393	4	269
Warm Mix Asphalt	2064939	684	130	1119	1666	17968	422	2	126
Annual Emissions									
HMA (Control)	208579.7	45.6	12.4	130.8	111.0	1787.9	33.1	0.1	8.4
HMA with RAP	203122.7	44.8	12.1	127.9	105.4	1787.4	32.5	0.1	8.3
HMA with RAS	194222.2	39.7	11.6	126.2	110.3	1766.3	29.7	0.1	7.2
Porous Asphalt	279319.0	63.7	17.0	164.2	155.4	1803.7	44.8	0.2	11.7
Pervious Concrete	222621.4	66.4	15.7	187.2	132.9	91.6	69.7	0.2	13.4
Warm Mix Asphalt	137662.6	45.6	8.7	74.6	111.0	1197.9	28.1	0.1	8.4
Percent Compared to Control									
HMA (Control)	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
HMA with RAP	2.62%	1.80%	2.67%	2.21%	5.07%	0.03%	1.77%	0.21%	1.39%
HMA with RAS	6.88%	12.99%	6.48%	3.57%	0.68%	1.21%	10.23%	17.89%	13.89%
Porous Asphalt	-33.91%	-39.83%	-37.27%	-25.53%	-39.93%	-0.88%	-35.41%	-38.80%	-39.25%
Pervious Concrete	-6.73%	-45.61%	-26.60%	-43.09%	-19.71%	94.88%	-110.52%	-32.13%	-59.77%
Warm Mix Asphalt	34.00%	0.00%	30.00%	43.00%	0.00%	33.00%	15.00%	0.00%	0.00%

Table 3.6 – Rehabilitation Expected Service Lives

Process	Life Span
Mill and HMA Overlay (Control)	11
Mill and HMA Overlay with RAP	11
Cold In-Place Recycling	11
CIREAM	11
Full Depth Reclamation	15
Microsurfacing	8

Table 3.7 displays the PaLATE results of the six analysed rehabilitation techniques under the local road classification. Similar tables for all other road classifications are located within Appendix C. The results indicate that M&O is the least environmentally friendly rehabilitation technique. The environmental impacts of M&O can be reduced by including RAP. The results for CIP and CIREAM are very similar; the difference is due to CIREAM using expanded asphalt instead of the emulsified asphalt of CIP. The most environmentally friendly option is microsurfacing. However, microsurfacing is a surface treatment technique; therefore it is not necessarily applicable in circumstances with excessive pavement deterioration. Excluding microsurfacing, full depth reclamation resulted with the lowest energy and water consumption and the lowest emissions in all criteria.

The PaLATE output is divided into three categories which are materials transportation, materials production and processes (equipment). Material transportation accounts for the emissions released during the transportation of material to and from the site. Material production accounts for the emissions released during the production of the materials. Processes accounts for the emissions released by the construction equipment during pavement construction. Majority of emissions occur during material production. Figure 3.1 displays the bar chart for the nitrous oxide emissions criterion under the local road classification; similar bar charts for all criteria under all road classifications are located within Appendix C.

Table 3.7 – Local Road Rehabilitation PaLATE Results

Process	Energy [MJ]	Water Consumption [kg]	CO_2 [Mg] = GWP	NO_x [kg]	PM_{10} [kg]	SO_2 [kg]	CO [kg]	Hg [g]	Pb [g]
Total Emissions									
Mill and HMA Overlay (Control)	1911072	515	99	978	536	26699	320	1.94	99
Mill and HMA Overlay with RAP	1829217	503	94	934	452	26692	311	1.93	97
Cold In-Place Recycling	1005884	318	54	475	206	9826	194	1.24	61
CIREAM	1056090	339	57	491	209	9841	206	1.33	65
Full Depth Reclamation	668770	179	35	349	188	9275	113	0.67	34
Microsurfacing	137092	35	7	83	48	2272	35	0.20	10
Annual Emissions									
Mill and HMA Overlay (Control)	173733.8	46.8	9.0	88.9	48.8	2427.2	29.1	0.18	9.0
Mill and HMA Overlay with RAP	166292.5	45.7	8.5	84.9	41.1	2426.6	28.3	0.18	8.8
Cold In-Place Recycling	91444.0	28.9	4.9	43.2	18.7	893.3	17.6	0.11	5.5
CIREAM	96008.1	30.8	5.1	44.6	19.0	894.6	18.7	0.12	5.9
Full Depth Reclamation	44584.7	11.9	2.3	23.3	12.5	618.3	7.5	0.04	2.3
Microsurfacing	17136.5	4.4	0.9	10.4	6.0	284.0	4.3	0.03	1.3
Percent Compared to Control									
Mill and HMA Overlay (Control)	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Mill and HMA Overlay with RAP	4.28%	2.39%	5.02%	4.43%	15.77%	0.03%	2.75%	0.23%	1.78%
Cold In-Place Recycling	47.37%	38.34%	45.59%	51.39%	61.56%	63.20%	39.36%	35.95%	38.47%
CIREAM	44.74%	34.25%	42.71%	49.77%	61.06%	63.14%	35.60%	31.33%	34.25%
Full Depth Reclamation	74.34%	74.53%	74.25%	73.82%	74.35%	74.53%	74.06%	74.53%	74.53%
Microsurfacing	90.14%	90.68%	89.90%	88.34%	87.65%	88.30%	85.08%	85.79%	85.36%

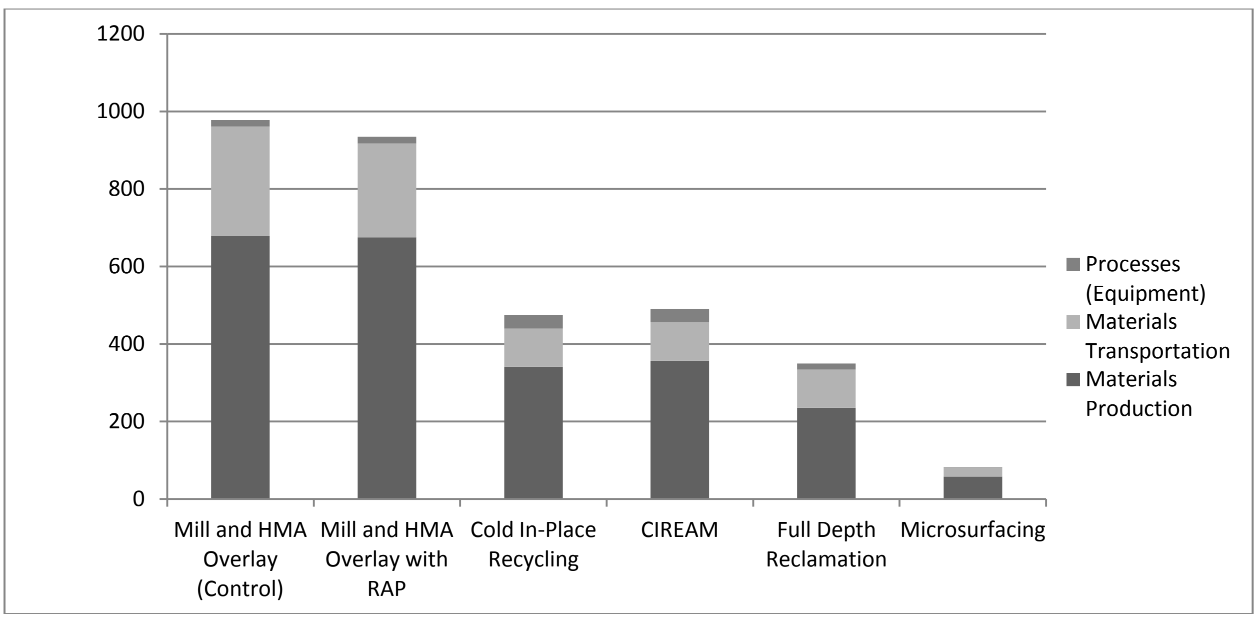


Figure 3.1 – Nitrous Oxide Emissions of the Analyzed Rehabilitation Techniques

3.2.4. Carbon Footprinting

For the purpose of this research, the carbon footprint of a pavement project is defined as the total amount of Greenhouse Gases (GHG) emitted throughout all phases; from planning and programming to decommission. A GHG is defined as a gas that contributes to global warming by trapping heat radiation within the earth's atmosphere. Several types of gases are considered GHG, however carbon footprinting is often expressed as the amount of CO_2 equivalent. Minimizing the carbon footprint of a project is a significant component of sustainability. "Combating the effects of climate change by mitigating GHG emissions and implementing adaptive measures is of paramount concern to the global community" [Monkman, 2010]. In response, significant efforts have been made to reduce the CO_2 emissions of the transportation industry.

Carbon footprints are traditionally expressed in terms of CO_2 equivalence. To determine the CO_2 equivalence of a specific GHG, the mass of the GHG must be multiplied by its corresponding Global Warming Potential (GWP). The GWP compares the amount of heat trapped by a certain mass of the GHG in question to the amount of heat trapped by an equivalent mass of CO_2 over an X amount of years. For example, carbon monoxide has a 100 year GWP of 3 which means 1kg of carbon monoxide warms the atmosphere 3 times as much as 1kg of carbon dioxide over the next 100 years [Aprovecho Research Center, 2007]. GWP's are provided for 20, 100 and 500 year periods; for the purposes of carbon footprinting the 100 year GWP is considered the accepted period [IPCC, 2007].

This section of the thesis summarizes the carbon footprinting analysis results. The environmental saving quantification results were utilized for obtaining the GHG emission quantities of several construction and maintenance and rehabilitation techniques. Table 3.1 displays the evaluated pavement technologies in this project. These were selected for the City of Markham given they are available for possible usage. The Intergovernmental Panel on Climate Change published an article presenting the GWP of all GHG's; Table 3.8 displays the 100 year GWP of some key greenhouse gases; a full list of 100 year GWP for all GHG's are located within Appendix D.

Table 3.8 – Global Warming Potential's of key Greenhouse Gases [IPCC, 2007]

Greenhouse Gas	Global Warming Potential
Carbon Dioxide	1
Carbon Monoxide	3
Methane	21
Nitrous Oxide	310
Hydroflourocarbon-23 (CHF3)	11700
Perfluorinated compound (CF4)	6500
Sulfur hexafluoride	23,900

Pavement construction and maintenance emits five typical gases that impact global climate factors; these gases are CO_2, CO, NO_x, PM_{10} and SO_2. Carbon dioxide is the most abundant greenhouse gas and is used as the reference GHG in the carbon footprint calculation.

Within the atmosphere, carbon monoxide has a life span of several months before it naturally coverts into carbon dioxide; the 100 year GWP of carbon monoxide is 3. Carbon monoxide itself is not a greenhouse gas; however, it's assigned a GWP of 3 since its presence in the atmosphere increases the lifespan of methane (which is a GHG) by reducing the amount of radical OH molecules [Aprovecho Research Center, 2007].

Oxides of nitrogen (NO_x) are presently believed to be greenhouse neutral. However, its presence within the atmosphere affects the atmospheric chemistry in complex ways including acid rain, disrupting ozone chemistry and interacting with radical OH molecules [Aprovecho Research Center, 2007].

Particulate Matter (PM) is composed of miniscule solid and water particles which can absorb or scatter sunlight when suspended within the earth's atmosphere. Different types of PM scatter and absorb sun light to varying degrees which is defined by their Single Scattering Albedo (SSA). The lower the SSA of the particulate matter the more sunlight it absorbs. Even though PM can absorb sunlight and therefore warm the atmosphere, it is not part of the Kyoto agreement and is therefore not considered a GHG [Aprovecho Research Center, 2007].

Sulphur dioxide (SO_2) has several effects on the global climate at varying levels of emission. At low levels, SO_2 can actually reduce the global surface temperature by approximately 0.5°C. At these levels the SO_2 is oxidized into sulphuric acid within weeks. However, with higher emissions the atmospheres oxidizing capacity is exceeded which leads to very rapid warming. Current levels are significantly below either of these points; in addition SO_2 emissions have been greatly reduced in the past few decades in an attempt to mitigate acid rain. SO_2 is not considered a GHG [Ward, 2009].

The carbon footprinting results for the local road classification are displayed in Table 3.9. Similar tables for other City of Markham road classifications are located within Appendix C.

Under the initial construction category, Warm Mix Asphalt (WMA) resulted with the lowest carbon footprint while porous asphalt resulted with the highest. Porous asphalt also emitted the largest quantities of PM_{10}, and SO_2 and the second largest quantity of NO_x. Pervious concrete emitted the most NO_x. Both porous asphalt and pervious concrete resulted with larger carbon footprints than the control. This is due to the nature of concrete and due to the larger quantity of bitumen utilized by porous asphalt. The carbon footprint of asphalt pavement can be slightly reduced with the utilization of reclaimed asphalt pavement or recycled asphalt shingles.

Under the maintenance and rehabilitation category, microsurfacing resulted with the lowest carbon footprint and NO_x, PM_{10}, and SO_2 emissions. However, microsurfacing is a surface treatment technique; therefore it is not necessarily applicable in circumstances with excessive pavement deterioration. Excluding microsurfacing, full depth reclamation resulted with the lowest carbon footprint and emissions in all criteria. As observed in initial construction, including RAP within the asphalt mix reduces the carbon footprint of asphalt technologies. CIP recycling and CIREAM both resulted with a significantly lower carbon footprint than the mill and overlay control option; with CIP recycling having a slight edge over CIREAM. The control technology resulted with the largest carbon footprint and emissions in all criteria.

Table 3.9 – Local Road Carbon Footprinting Analysis Results

Process	CO_2e	NO_x [kg]	PM_{10} [kg]	SO_2 [kg]
Initial Construction				
HMA (Control)	12505	131	111	1788
HMA with RAP	12172	128	105	1787
HMA with RAS	11690	126	110	1766
Porous Asphalt	17163	164	155	1804
Pervious Concrete	15915	187	133	92
Warm Mix Asphalt	8768	75	111	1198
Maintenance and Rehabilitation				
Mill and HMA Overlay (Control)	9071	89	49	2427
Mill and HMA Overlay with RAP	8618	85	41	2427
Cold In-Place Recycling	4941	43	19	893
CIREAM	5203	45	19	895
Full Depth Reclamation	2336	23	13	618
Microsurfacing	921	10	6	284

3.3. Economical Savings

For the purpose of this research, the PaLATE program was utilized for quantifying the economical savings of various pavement technologies. PaLATE allows the user to specify project expenses in either a lump sum format or a unit price format. The unit price format requires the user to specify labour and equipment costs, expected profit margin in addition to material unit prices. PaLATE allows users to change the discount rate applied in the Life Cycle Cost Analysis (LCCA). In addition, PaLATE supports two scenarios allowing the user to compare two competing alternative projects. The second scenario can also be used for the purposes of conducting a sensitivity analysis for a single alternative by changing only the discount rate. PaLATE can conduct a LCCA up to 40 years. Appendix A provides a walkthrough of PaLATE providing new users an opportunity to become familiar with the program.

The economical quantification encompasses the same pavement technologies evaluated in the environmental quantification section. In order to estimate the economic impact of the listed technologies, PaLATE requires user input falling under two categories; pavement layer specifications and material/process costs. PaLATE was developed in the United States therefore all units must be converted into imperial units for calculation. Table 3.1 displays the evaluated pavement technologies.

3.3.1. PaLATE Input

The pavement layer specification worksheet describes the pavement dimensions (width, length and depth) of each layer from wearing course to subbase. City of Markham roads fall under five working classifications which are: industrial, laneway, local, major collector and minor collector. Pavement width and depth depend on the road classification while a control length of 1.0 km was assumed for this study. Table 3.2 displays the pavement dimensions of all five City of Markham road classifications [TOM, 2011]. In addition to pavement dimensions, this worksheet allows users to input material and process densities. The default values provided by PaLATE were used for the purposes of this project. Designs for all analysed pavement technologies are presented in Appendix B.

The second worksheet, material/process costs, requires the user to input project expenditures in either a lump sum format or a unit cost format. The City of Markham uses the lump sum format therefore this format was adopted for the economic analysis. The City of Markham provided cost data for the pavement technologies they currently employ. Cost data for the pavement technologies not employed by the City, excluding pervious concrete and porous asphalt, was obtained from the 2010 study entitled "Quantifying Pavement Sustainability" which was completed for the Ontario Ministry of Transportation. Lump sum cost estimates for pervious concrete and porous asphalt were obtained from Dufferin Construction. The cost data provided was converted from \$/tonne to \$/yd^3 or \$/yd^2 using the assumed densities provided by PaLATE. Table 3.10 displays the provided cost data for all rehabilitation techniques analysed and Table 3.11 displays the provided initial construction cost data [TOM, 2012] [Chan, 2010] [Rigatti, 2012].

3.3.2. PaLATE Output

This section presents a summary of the PaLATE economic analysis results; detailed numerical results are located in Appendix E. Traditional HMA is adopted as the initial construction control technology and Mill and Overlay as the rehabilitation control technology; all other technologies are compared to these two control values. The conducted PaLATE analysis is grouped into five categories which are the five road classification; industrial, laneway, local, major collector and minor collector. Each pavement technology displayed in Table 3.1 is analysed under all five road classifications. All pavement designs are based on the specifications provided by the City of Markham and are located in Appendix B [TOM, 2011].

Table 3.10 – Rehabilitation Cost Data [TOM, 2012] [Chan, 2010]

Mill and Overlay (Control)		
Item	Unit Cost	Units
Asphalt Overlay	\$ 109.42	\$/yd^3
Strip Existing Asphalt (100mm)	\$ 4.31	\$/yd^2

Mill and Overlay with RAP		
Item	Unit Cost	Units
Asphalt Overlay	\$ 109.42	\$/yd^3
RAP	\$ 30.45	\$/yd^3
Strip existing asphalt (100mm)	\$ 4.31	\$/yd^2

Microsurfacing		
Item	Unit Cost	Units
Microsurfacing	\$ 2.82	\$/yd^2

CIREAM		
Item	Unit Cost	Units
Asphalt Overlay	\$ 109.42	\$/yd^3
CIREAM	\$ 11.80	\$/yd^2

Full Depth Reclamation		
Item	Unit Cost	Units
Asphalt Overlay	\$ 109.42	\$/yd^3
FDR	\$ 5.10	\$/yd^3

CIP		
Item	Unit Cost	Units
Asphalt Overlay	\$ 109.42	\$/yd^3
CIP	\$ 8.03	\$/yd^2

Table 3.11 – Initial Construction Cost Data [TOM, 2012] [Chan, 2010] [Rigatti, 2012]

HMA (Control)		
Item	**Unit Cost**	**Units**
Asphalt Overlay	$ 109.42	$/yd^3
Granular A	$ 25.50	$/yd^3
Granular B	$ 22.50	$/yd^3

HMA with RAP		
Item	**Unit Cost**	**Units**
Asphalt Overlay	$ 109.42	$/yd^3
RAP	$ 30.45	$/yd^3
Granular A	$ 25.50	$/yd^3
Granular B	$ 22.50	$/yd^3

Porous Asphalt		
Item	**Unit Cost**	**Units**
Asphalt Overlay	$ 172.03	$/yd^3
OGDL	$ 34.00	$/yd^3

Warm Mix Asphalt		
Item	**Unit Cost**	**Units**
WMA Overlay	$ 118.95	$/yd^3
Granular A	$ 25.50	$/yd^3
Granular B	$ 22.50	$/yd^3

Pervious Concrete		
Item	**Unit Cost**	**Units**
Pervious Concrete	$ 488.44	$/yd^3
OGDL	$ 34.00	$/yd^3

HMA with RAS		
Item	**Unit Cost**	**Units**
Asphalt Overlay	$ 109.42	$/yd^3
RAS	$ 80.84	$/yd^3
Granular A	$ 25.50	$/yd^3
Granular B	$ 22.50	$/yd^3

The output provided by PaLATE contains four pieces of information which are: Initial Construction Net Present Value (NPV), Maintenance NPV, Initial Construction Annualized Cost (AC) and Maintenance AC. For the purposes of this project the annualized costs are calculated based on a 40 year analysis period; for the purposes of remaining conservative a discount rate of 6% is chosen.

For comparison purposes, the PaLATE results of each rehabilitation technique are converted into equivalent annual costs. Service lives are obtained from the (TAC) Pavement Design and Management Guide [TAC, 2012]. The Guide provided a range of expected service lives for each rehabilitation technique instead of a fixed number. Therefore, the average of each range is assumed as the service life of the pavement technology in question. Table 3.12 displays the services lives of all evaluated pavement technologies.

Table 3.13 displays the economic analysis results for all initial construction technologies under the local road classification. Similar tables for all road classifications are located with Appendix E; the conclusions made based on Table 3.13 are valid for all road classifications. Pervious concrete was the most expensive initial construction technology followed by porous asphalt; porous asphalt is approximately 30% cheaper than pervious concrete. Hot Mix Asphalt with RAP and HMA with RAS are slightly less expensive than the control while Warm Mix Asphalt is slightly more expensive. The costs displayed in Table 3.13 are initial construction costs and do not account for the maintenance and rehabilitation procedures required during the pavement life cycle. A Life Cycle Cost Analysis (LCCA) must be completed to fully compare the costs associated with the evaluated pavement construction technologies.

Table 3.12 – Pavement Technology Service Lives [TAC, 2012]

Process	Life Span
HMA (Control)	15
HMA with RAP	15
HMA with RAS	15
Porous Asphalt	15
Pervious Concrete	20
Warm Mix Asphalt	15
Mill and HMA Overlay (Control)	11
Mill and HMA Overlay with RAP	11
Cold In-Place Recycling	11
CIREAM	11
Full Depth Reclamation	15
Microsurfacing	8

Table 3.14 displays the economic analysis results for all rehabilitation technologies under the local road classification. Similar tables for all road classifications are located with Appendix E; the conclusions made based on Table 3.14 are valid for all road classifications. Mill and Overlay is the most expensive rehabilitation technology; however, including RAP within the asphalt overlay slightly reduces costs. Cold In-Place Recycling and CIREAM were both moderately expensive treatments with CIREAM being slightly more expensive. Microsurfacing was the cheapest of the evaluated technologies. However, microsurfacing is a surface treatment technology; therefore may not be applicable for roads with heavy degradation. Excluding microsurfacing, full depth reclamation was the cheapest rehabilitation technology.

3.4. Social Savings

The social cost of pavement projects is a significant aspect of sustainability since it addresses the impact projects have on road users and local residents. However, the social cost of projects is very difficult to quantify precisely. Individual pavement projects have different needs which must be uniquely addressed by stakeholders to achieve a socially sustainable pavement. In 2008, a Sustainable Pavement Workshop was held for the purposes of brainstorming pavement sustainability; attendees included CPATT, MTO, consultants and contractors [Chan 2010]. The following list was composed at the workshop:

- Emissions control in field construction, material manufacturing and while in use
- Perpetual pavement design (service life of 50 years)
- Maximizing the use of environmentally friendly materials
- Minimizing the project carbon footprint
- Use of alternative fuel sources
- Illustration of fuel and material conservation
- Improved material management (stockpiling)
- Improved water management
- Use of innovative materials, techniques and technologies
- Investment in sustainable technology research and development

Table 3.13 – Local Road Initial Construction PaLATE Results

Total				
Technology	Initial Construction NPV	Maintenance NPV	Initial Construction AC	Maintenance AC
HMA (Control)	$ 257,037.00	$ -	$ 17,083.00	$ -
HMA with RAP	$ 239,564.00	$ -	$ 15,922.00	$ -
HMA with RAS	$ 255,278.00	$ -	$ 16,966.00	$ -
Porous Asphalt	$ 389,862.00	$ -	$ 25,911.00	$ -
Pervious Concrete	$ 744,233.00	$ -	$ 49,463.00	$ -
Warm Mix Asphalt	$ 269,191.00	$ -	$ 17,891.00	$ -

Annual				
Technology	Initial Construction NPV	Maintenance NPV	Initial Construction AC	Maintenance AC
HMA (Control)	$ 17,135.80	$ -	$ 1,138.87	$ -
HMA with RAP	$ 15,970.93	$ -	$ 1,061.47	$ -
HMA with RAS	$ 17,018.53	$ -	$ 1,131.07	$ -
Porous Asphalt	$ 25,990.80	$ -	$ 1,727.40	$ -
Pervious Concrete	$ 37,211.65	$ -	$ 2,473.15	$ -
Warm Mix Asphalt	$ 17,946.07	$ -	$ 1,192.73	$ -

Table 3.14 – Local Road Rehabilitation PaLATE Results

Total				
Technology	Initial Construction NPV	Maintenance NPV	Initial Construction AC	Maintenance AC
Mill and Overlay (Control)	$ -	$ 260,603.00	$ -	$ 17,320.00
Mill and Overlay with RAP	$ -	$ 243,963.00	$ -	$ 16,214.00
Cold In-Place Recycling	$ -	$ 130,033.00	$ -	$ 8,642.00
CIREAM	$ -	$ 168,325.00	$ -	$ 11,187.00
Full Depth Reclamation	$ -	$ 56,959.00	$ -	$ 3,786.00
Microsurfacing	$ -	$ 28,643.00	$ -	$ 1,904.00

Annual				
Technology	Initial Construction NPV	Maintenance NPV	Initial Construction AC	Maintenance AC
Mill and Overlay (Control)	$ -	$ 23,691.18	$ -	$ 1,574.55
Mill and Overlay with RAP	$ -	$ 22,178.45	$ -	$ 1,474.00
Cold In-Place Recycling	$ -	$ 11,821.18	$ -	$ 785.64
CIREAM	$ -	$ 15,302.27	$ -	$ 1,017.00
Full Depth Reclamation	$ -	$ 3,797.27	$ -	$ 252.40
Microsurfacing	$ -	$ 3,580.38	$ -	$ 238.00

- Providing proper employee training
- Providing quality assurance and quality control
- Proactive new construction and maintenance planning
- Minimizing user delays during construction
- Minimizing noise pollution during construction and while in use
- Accommodating for unique local development (ex: retirement home)

The above list provides a starting point when considering the social costs of pavement projects. When attempting to minimize the social impact of a specific pavement project, the unique characteristics of the immediate location must be adequately accommodated through sound engineering judgement.

3.5. Chapter 3 Summary

The objective of this chapter was to assess and evaluate the environmental and economic savings when utilizing different initial construction and rehabilitation pavement technologies. This evaluation is broken down into four categories which are environmental, economic, social, and carbon footprinting.

The most environmentally friendly initial construction and rehabilitation techniques are warm mix asphalt and microsurfacing, respectively. Microsurfacing is however a surface treatment technique and may therefore not be applicable on heavily deteriorated roads. Excluding microsurfacing, full depth reclamation is the most environmentally friendly rehabilitation technique. The same initial construction and rehabilitation pavement technologies resulted with the lowest carbon footprints. Including RAP and RAS mix designs reduces the environmental impact and carbon footprint of traditional hot mix asphalt.

The costs provided in this summary are for the local road classification. Hot mix asphalt with RAP resulted with the lowest initial construction cost (equivalent annual worth (EAW) of $15,970.93) while pervious concrete was the most expensive (EAW of $37,211.65). Warm mix asphalt resulted with a slightly higher construction cost (EAW of $17,946.07) when compared to traditional hot mix asphalt (EAW of $17,155.80). Porous asphalt is approximately 30% cheaper than pervious concrete. Mill and overlay was the most expensive rehabilitation technology (EAW of $23,691.18) while full depth reclamation was the least expensive (EAW of $3,797.27). Including RAP slightly reduces the costs associated with mill and overlay.

The social aspect of sustainability is difficult to quantify due to its arbitrative nature. Individual pavement projects have different needs which must be uniquely addressed by stakeholders to achieve a socially sustainable pavement. This chapter briefly presented some initial metrics for quantifying social costs.

Chapter 4
SUSTAINABILITY RATING SYSTEMS EVALUATION

4.1. Introduction

The objective of this chapter is to conduct an in depth examination of GreenPave as a potential system for incorporating sustainable best practices into the City of Markham pavement operations. GreenPave was chosen as the preferred sustainability rating system because it was developed by the MTO and has been tailored to Ontario's climate, standards and legislations. Therefore, GreenPave is the most compatible rating system for the City Of Markham. Incorporation is considered for both the network and project levels; however this chapter emphasizes the project level. A pilot project will be designed and performed; this pilot project applies the GreenPave rating system to all pavement technologies evaluated in a previous chapter of this thesis. The local road classification pavement designs were adopted for this GreenPave evaluation. The results of this pilot project will be presented and assessed.

4.2. GreenPave

This section of the report presents a brief review of the GreenPave rating system. GreenPave is defined as a "simple points based rating system designed to assess the "greenness" of pavement" [Lane, 2011]. The main objective of GreenPave is to provide a rating system for assessing the sustainability of pavement design and construction projects. GreenPave is based on GreenLITES, Greenroads and LEED® but is customized for Ontario climates, standards and legislations. The main difference between GreenPave and competing systems is that GreenPave focuses specifically on pavement projects instead of the entire road; GreenPave is applicable to both flexible and rigid pavements. There are four categories within the GreenPave program and each category is further divided into subcategory credits. Figure 4.1 displays an overview of the GreenPave categories and subcategories and the points associated with each criterion.

There is a total of 32 points available under the GreenPave point system. Project may be awarded points between 0 and the specified maximum based on the degree at which credit objectives are met. GreenPave developers propose achievement levels similar to the GreenLITES system. The GreenPave achievement levels and their corresponding point ranges are as follows: [Lane, 2011]

- Non-Certified 0 – 9 points
- Bronze Certified 10 – 14 points
- Silver Certified 15 – 19 points
- Gold Certified >=20 points
- Trillium Certified Future development

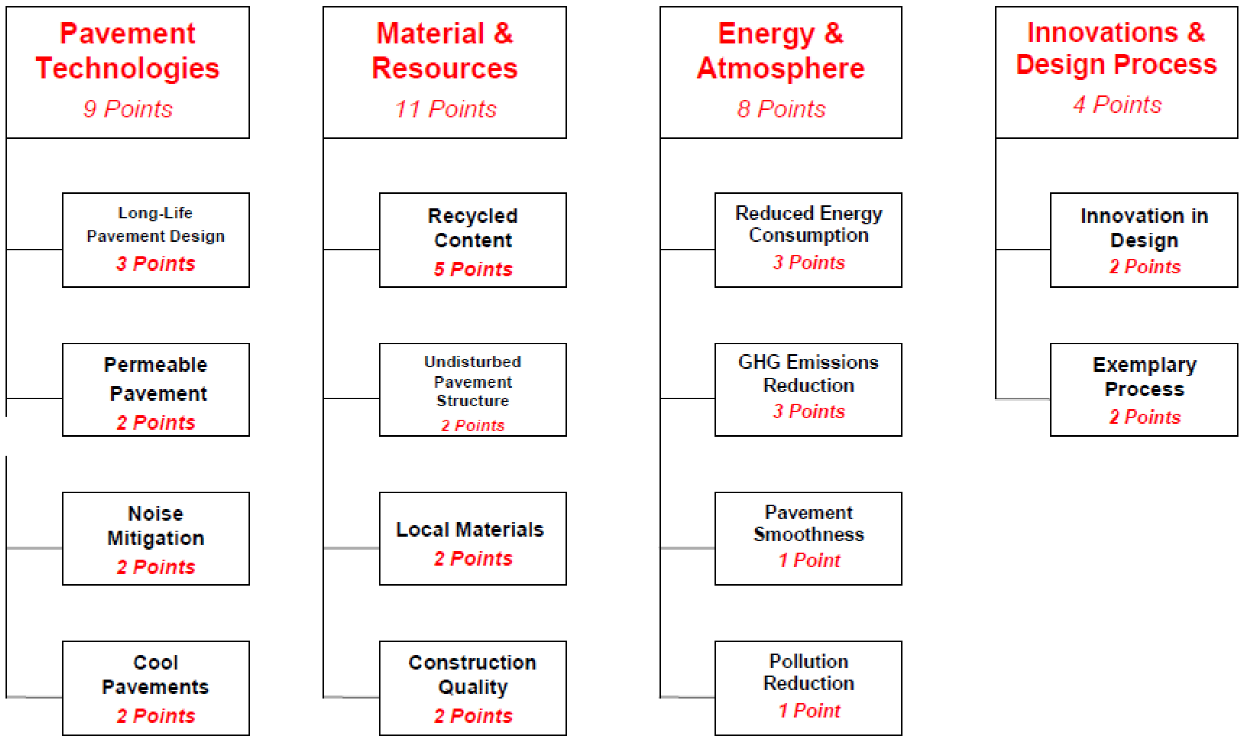


Figure 4.1 – GreenPave Scorecard Overview [Lane, 2011]

4.3. GreenPave Evaluation

This section of the report presents an example project which is evaluated using GreenPave for the purpose of illustrating the GreenPave evaluation methodology. The example project is an initial construction Hot Mix Asphalt (HMA) pavement with Reclaimed Asphalt Pavement (RAP) designed according to City of Markham specifications under the local road classification. Table 4.1 displays the HMA with RAP pavement design; a control length of 1 km was assumed.

Table 4.3 displays the reference guide used to evaluate pavement projects using GreenPave. The project in question is awarded points based on the specified requirements. The example pavement does not meet any of the requirements within the Long Life Pavement or Permeable Pavement subcategories therefore 0 points are awarded. The wearing course is composed of 40mm of Superpave 12.5 therefore 1 point is awarded under the Noise Mitigation subcategory. Once again the pavement does not meet the requirements under the Cool Pavement subcategory therefore 0 points are awarded.

The Recycled Content subcategory requires a weighted average to determine the quantity of points awarded since the different pavement layers earned varying amounts of points. Table 4.2 displays the weighted average calculation; therefore 2.7 points are awarded under the recycled content subcategory. No points are awarded under the Reuse of Pavement subcategory since an initial construction project is being evaluated. All utilized materials have transportation distances less than 100km therefore 2 points are awarded under the Local Materials subcategory. Quality assurance and quality control ensures the completed pavement meets requirements therefore 1 point is awarded under the Construction Quality subcategory.

A weighted average is required for both the Reduce Energy and GHG Emissions Reduction subcategories; the method for calculating the awarded points is identical to the method illustrated in Table 4.2. Both subcategories results with 1.1 points being awarded. No points are awarded under the Pollution Reduction subcategory since neither requirement is met. The Innovation in Design and Exemplary Process subcategories are reserved for extraordinary cases; therefore no points are awarded in either subcategory.

Table 4.1 – HMA with RAP Pavement Design

Process	Initial or Maint.	Layer	Material	Percent	Layer Depth (mm)	Width (m)
Asphalt with 20%/15% RAP	Initial	Wearing Course 1 (Superpave 12.5)	Virgin Aggregate	80.75	40	8.5
			RAP	14.25		
			Bitumen	5		
		Wearing Course 2 (Superpave 19.0)	Virgin Aggregate	76	75	
			RAP	19		
			Bitumen	5		
		Subbase 1 (Granular A)	RAP to site	30	150	
			Gravel to site	70		
		Subbase 2 (Granular B)	RAP to site	30	300	
			Rock to Site	70		

Table 4.2 – Recycled Content Calculation

Pavement Later	Points Awarded	Thickness	Thickness X Points
Wearing Course 1	1	40	40
Wearing Course 2	2	75	150
Granular A	3	150	450
Granular B	3	300	900
	Total:	565	1540
	Awarded Points	1540/565=	2.7

Table 4.4 displays a completed GreenPave scorecard for the provided example. In this case, the evaluated project scored a total of 9.9 points; therefore the project would not receive any certification. Detailed scorecard results for all evaluated pavement technologies are located within Appendix F.

Table 4.3 – GreenPave Rating System Guide [GreenPave, 2012]

Sub-Category	Points Awarded	Requirements		
		Asphalt	Concrete	Granular Layer
Long Life Pavement	2	Composite pavement, perpetual asphalt pavement, deep strength asphalt pavement	-	-
	3	-	Rigid pavement	-
Permeable Pavement	1	Roadside drainage		-
	2	Parking lot		-
Noise Mitigation	1	Superpave mixes	Longitudinal tining, Diamond grinding	-
	2	SMA mixes, HMA with rubber modified AC, Quiet Pavement Mixes	-	-
Cool Pavement	1	Quiet pavement, porous asphalt	-	-
	2	-	Concrete pavement, white cement pavement, permeable pavers, pervious concrete	-
Recycled Content	1	5-15% RAP by mass	10-15% of SCM by mass of cement	10-29% RM by mass
	2	16-20% RAP by mass	16-25% of SCM by mass of cement	-
	3	21-30% RAP by mass	-	30-49% RM by mass
	4	31-40% RAP by mass	-	-
	5	CIR, CIREAM, HIR	-	>50% RM by mass, In-place processing
	Extra Point	>1% of CR or RST by mass	Use of slurry water or treated wash water	-
Reuse of Pavement	1	Preservation treatments		-
	2	Maintainingg >80% of pavement structure, Concrete overlay		-
Local Materials	1	50-79% materials transported less than 100 km		
	2	>80% materials transported less than 100 km		
Construction Quality	1	Meets Requirements		
	2	Exceeds Requirements		
Reduce Energy Consumption	1	WMA, 5-15% RAP, >2% RST by mass	16-25% SCM by mass of cement	10-49% RM by mass
	2	HIR, 16-40% RAP by mass	-	>50% RM by mass, In-place processing
	3	CIR, CIREAM	-	FDR, EAS
GHG Emissions Reduction	1	WMA, 5-15% RAP by mass	16-25% SCM by mass of cement	10-49% RM by mass
	2	HIR, 16-40% RAP by mass	-	>50% RM by mass, In-place processing
	3	CIR, CIREAM	-	FDR, EAS
Pavement Smoothness	1	IRI < 0.65	Concrete	-
Pollution Reduction	1	>50% vehicles with diesel retrofit	>25% vehicles with alternative fuels	-
Innovation in Design	1	1 innovation in design		
	2	> 2 innovations in design		
Exemplary Process	1	1 exemplary process		
	2	>2 exemplary processes		

Table 4.4 – Sample GreenPave Scorecard

Category	Sub-Category	Max Points	Awarded Points
Pavement Technologies	Long Life Pavement	3	0
	Permeable Pavement	2	0
	Noise Mitigation	2	1
	Cool Pavement	2	0
Materials & Resources	Recycled Content	5	2.7
	Reuse of Pavement	2	0
	Local Materials	2	2
	Construction Quality	2	1
Energy & Atmosphere	Reduce Energy Consumption	3	1.1
	GHG Emissions Reduction	3	1.1
	Pavement Smoothness	1	1
	Pollution Reduction	1	0
Innovations & Design Processes	Innovation in Design	2	0
	Exemplary Process	2	0
	Total:	32	**9.9**

4.4. Green Discounted Life Cycle Cost (GDLCC)

This section of the thesis presents the GreenPave evaluation results; the pavement technologies analysed in the literature review of this thesis were adopted for this evaluation. The intent is to provide the City of Markham with anticipated GreenPave evaluation results for these newer technologies that they are currently using.

Table 4.5 displays the results of GreenPave evaluation for all initial construction and rehabilitation technologies. Under the initial construction category, pervious concrete resulted with the highest GreenPave score while HMA with RAS and porous asphalt resulted with the lowest. HMA, HMA with RAP and porous asphalt were not certified, while pervious concrete, HMA with RAS and warm mix asphalt received bronze certification. Including RAP within HMA slightly increased the GreenPave score.

Under the rehabilitation category, CIP, CIREAM and FDR were all tied for the highest GreenPave score, while microsurfacing and mill and overlay were tied for the lowest. Unlike the RAP observation made under initial construction, including RAP within Mill and Overlay significantly increased the GreenPave score. This is due to the Energy Consumption and GHG Emissions reductions subcategories. The inclusion of RAP within HMA and mill and overlay increased their respective scores by 0.6 and 4.4. CIP, CIREAM and FDR all received silver certification; the other technologies did not receive certification.

Table 4.5 – GreenPave Evaluation Results

Technology	GreenPave Score	Certification Level
HMA	9	Not Certified
HMA with RAP	9.9	Not Certified
HMA with RAS	10.2	Bronze
Porous Asphalt	7	Not Certified
Pervious Concrete	11	Bronze
WMA	10.4	Bronze

Technology	GreenPave Score	Certification Level
Mill and Overlay	5	Not Certified
M&O with RAP	9.4	Not Certified
CIP	16	Silver
CIREAM	16	Silver
FDR	16	Silver
Microsurfacing	5	Not Certified

The GreenPave rating system provides an opportunity for projects to be evaluated based on the environmental aspect of the sustainability triple bottom line. The economic aspect is not evaluated by GreenPave; therefore, to account for the economic aspect the MTO proposed the green discounted life cycle cost (GDLCC). The GDLCC allows the project evaluator to discount a certain percentage of the projects LCC based on its achieved GreenPave score. The higher the projects GreenPave score the larger the discounted percentage. The GDLLC is calculated mathematically according to the following formula: [Chan, 2010]

$$GDLCC = LCC - LCCxAx(\frac{GP}{32}) \qquad \text{[Equation 4.1]}$$

Where:
LCC = Life Cycle Cost of the project in question
GP = GreenPave points awarded to the project in question
A = Discount factor controlling the sensitivity of the GDLCC, MTO suggests a value of 0.2

For the purposes of this report a discount factor of 0.2 was utilized. The GDLCC formula was applied to the PaLATE Life Cycle Costs generated in chapter 3; Table 4.6 displays the results of the GDLCC analysis. The largest observed cost reductions occurred for CIP, CIREAM and FDR; the LCC of these three technologies were reduced by 10%. In this case, the pavement technologies are ranked in the same order (according to cost) before and after the GDLCC analysis. However, when comparing two alternatives with similar costs, the more expensive but more environmentally friendly option may become the more favourable alternative after applying the GDLCC.

Table 4.6 – GDLCC Analysis Results

Technology	GreenPave Score	Certification Level	GDLCC (A=0.2)
HMA	9	Not Certified	$ 242,578.67
HMA with RAP	9.9	Not Certified	$ 224,740.98
HMA with RAS	10.2	Bronze	$ 239,004.03
Porous Asphalt	7	Not Certified	$ 307,679.18
Pervious Concrete	11	Bronze	$ 693,066.98
WMA	10.4	Bronze	$ 251,693.59

Technology	GreenPave Score	Certification Level	GDLCC (A=0.2)
Mill and Overlay	5	Not Certified	$ 252,459.16
M&O with RAP	9.4	Not Certified	$ 229,630.17
CIP	16	Silver	$ 117,029.70
CIREAM	16	Silver	$ 151,492.50
FDR	16	Silver	$ 51,263.10
Microsurfacing	5	Not Certified	$ 27,747.91

The GDLCC provides a simple method for estimating the sustainability of competing alternatives; this provides decision makers with an important tool when faced with project level decisions. The GDLCC considers the economic and environmental aspects of the sustainability triple bottom line. The social costs of projects are typically very subjective which makes social cost quantification difficult. The research required to quantify projects social cost is beyond the scope of this project.

4.5. GDLCC Sensitivity Analysis

The discount factor (A) may be increased or decreased based on the value the user places on the environmental aspect of sustainability. A sensitivity analysis was conducted to determine to effect the discount factor has on the GDLCC results. The values of A used for the sensitivity analysis range from 0 to 0.5 at intervals of 0.1. A value of 0 represents the original LCC case with no green discount and a value of 0.5 allows for a maximum of 50% LCC reduction.

Figure 4.2 and Figure 4.3 display the sensitivity analysis results for initial construction and rehabilitation, respectively. Pervious concrete is excluded from Figure 4.2 due to very high costs when compared to the other five technologies. Tabular results of the sensitivity analysis presenting exact GDLCC values are located in Appendix F. Even at a discount factor of 0.5, none of the evaluated technologies becomes more preferable over any other technology. This suggests that the GDLCC analysis results are not overly sensitive to the discount factor magnitude. However, the highest observed GreenPave score in the analysed case was 16, which is only half of the available points. Projects with higher GreenPave scores will undergo more significant green discounts which may lead to different results. However, this is reasonable as one must note that GreenPave was developed by the MTO. Thus many of the weighting are directed at typical treatments used on high volume roads. Thus, some of the weighting and treatments may need to be adjusted in the future for the City of Markham usage.

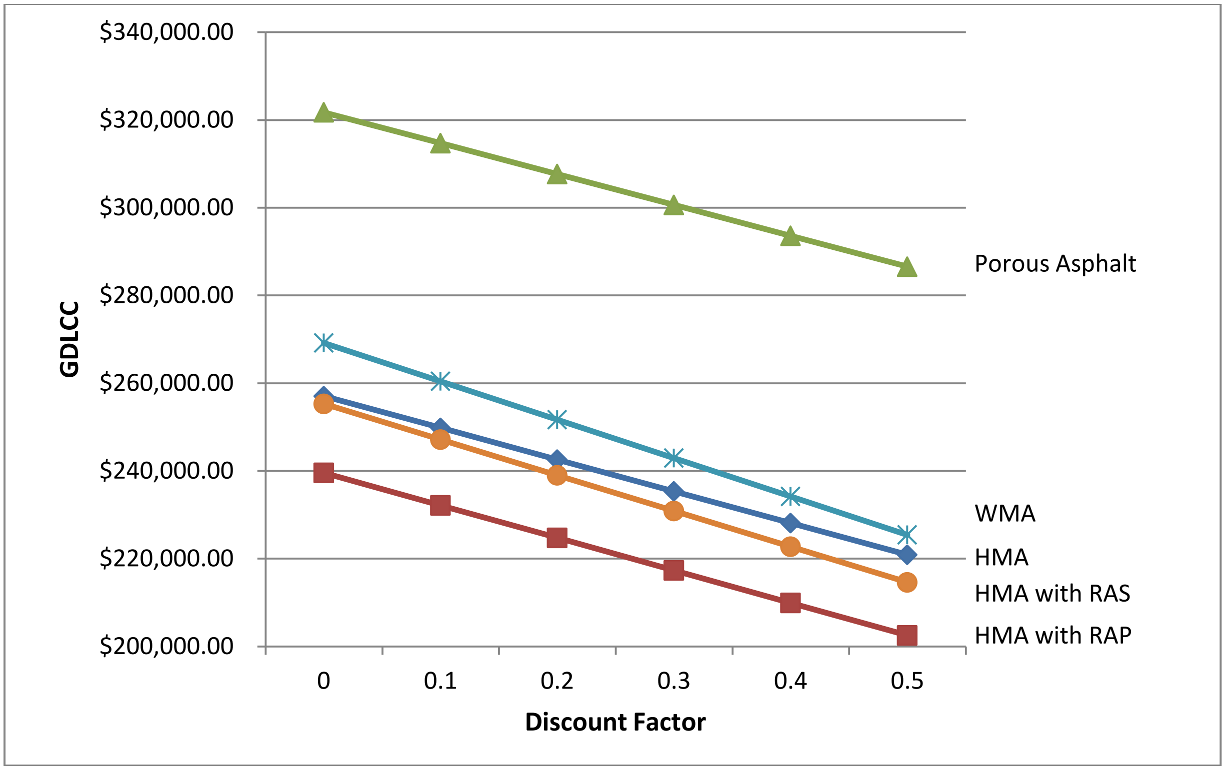


Figure 4.2 – Initial Construction Sensitivity Analysis Results

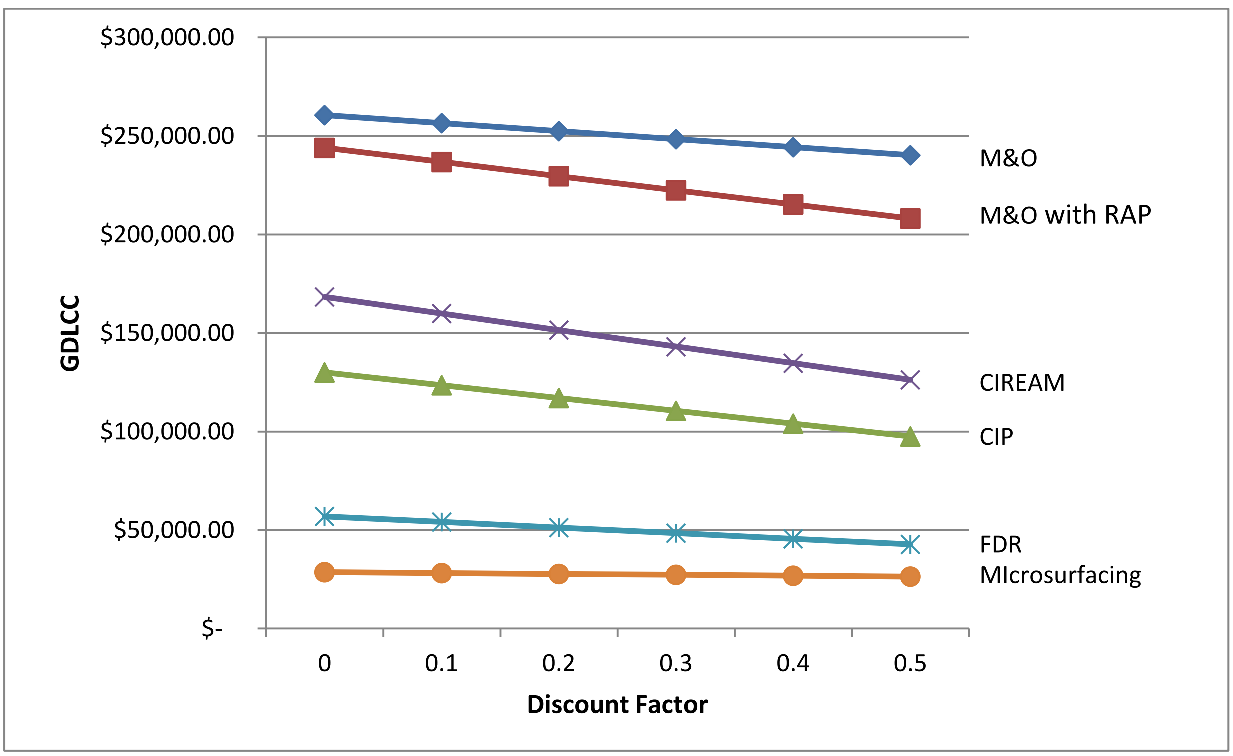


Figure 4.3 – Rehabilitation Sensitivity Analysis Results

4.6. Chapter 4 Summary

This chapter involved the examination of GreenPave as a potential system for incorporating sustainable best practices into the City of Markham pavement operations. GreenPave is applied to an example project to illustrate its methodology. The example project applies the GreenPave rating system to all pavement technologies identified. These include current technologies that are being used in the City and other potential technologies that could be adopted. Local road classification pavement designs were adopted for this evaluation. Under the initial construction category HMA with RAS, pervious concrete and warm mix asphalt resulted with bronze certification. Under the rehabilitation category, CIP, CIREAM and FDR all resulted with silver certification. All other technologies did not meet certification requirements. However, it is important to recognize that GreenPave was developed by MTO and given their road network is mainly high volume it may need to be adjusted in the future for applicability to the City of Markham.

GreenPave allows projects to be evaluated under the environmental aspect of sustainability. To account for the economical, the GDLCC is proposed where a portion of the projects LCC is discounted based on the achieved GreenPave score. All pavement technologies are evaluated under the GDLCC. HMA with RAP resulted with the lowest initial construction GDLCC while microsurfacing resulted with the lowest rehabilitation GDLCC. Excluding microsurfacing, FDR results with the lowest rehabilitation GDLCC.

Chapter 5
NETWORK AND PROJECT LEVEL FRAMEWORK DEVELPMENT

5.1. Introduction

The objective of this chapter is to develop a framework for incorporating sustainability into the project level and network level pavement engineering practices of the City of Markham. This evaluation includes the following components:

- Development of a project level framework,
- Review of current City of Markham network level practices,
- Review of MicroPAVER as a potential PMS for the City of Markham
- Network level pavement sustainability,
- Development of a network level framework.
- Network and project level framework connections

5.2. Project Level Framework Development

The GreenPave sustainability evaluation system will be the centrepiece of the recommended project level framework. Figure 5.1 displays the recommended seven step framework for achieving project level pavement sustainability.

The project level framework begins with the identification of maintenance and rehabilitation needs at specific road segments within the City of Markham road network. This need is determined at the network level by a Pavement Management System (PMS) through the use of several factors including Overall Condition Index (OCI), International Roughness Index (IRI) and budget. Once a specific site has been identified, several design alternatives should be generated. Designs can be generated in house or externally through consultants. Detailed pavement designs and expected Life Cycle Costs are required for each design for the GreenPave evaluation and GDLCC computation. Section 4.3 of this thesis provides detailed information outlining the design data required by GreenPave. These design alternatives are then evaluated using GreenPave and the GDLCC is computed. Using these results the City of Markham selects the most sustainable design alternative and the project proceeds into the construction phase.

The project will again be evaluated by GreenPave post construction to account for any design changes and potentially award credits in the innovation field; the GDLCC will be adjusted based on the updated GreenPave score. It is recommended that this GreenPave score should be stored in the PMS for future network level planning and programming.

5.3. Current City of Markham Network Level Practices

In order to develop a network level framework, the current network level practices at the City of Markham are reviewed; this section of the report presents the results of this review.

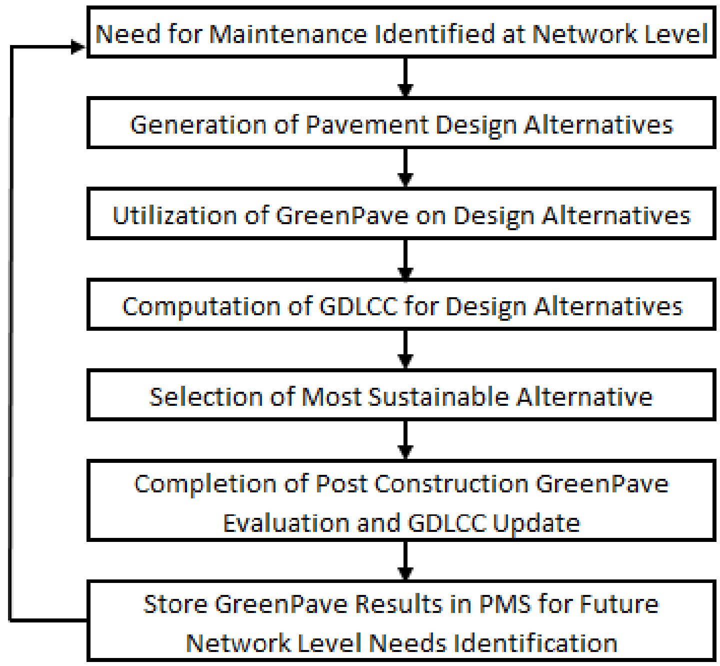


Figure 5.1 – Recommended Project Level Framework

The City of Markham starts their planning and programming roadwork by conducting field investigations to determine the current state of the entire road network. These field investigations are completed externally by a consultant every two to three years; the latest investigation was completed in September of 2011 by IMS. The data collected by the consultant is input into the City of Markham Hanson data base. The Hanson data base is not a Pavement Management System (PMS); it is used for data storage purposes only [Penner, 2012].

Using the pavement condition data, a map detailing the Overall Condition Index (OCI) of all City of Markham roads is generated. Road segments are grouped into three categories based on their current OCI: 0-60, 60-70 and 70-80. Segments with an OCI above 80 are not considered due to their very high level of service. The map generated for 2012 is located within Appendix G. Road segments are highlighted in red, blue and green representing segments with OCI between 0-60, 60-70 and 70-80 respectively. Based on this map, the City of Markham generates the road rehabilitation program for the year; this generation is completed manually through past experience. The road rehabilitation program for 2012 is located within Appendix G. Road segments with lower OCI are favoured over segments with higher OCI. Segments with slightly higher OCI may be chosen for rehabilitation if they are in close proximity to an extremely deteriorated segment; the purpose of this is to minimize costs and time associated with crew and equipment transportation [Penner, 2012].

Once a segment is chosen for rehabilitation, a crew is dispatched to the site to perform a detailed evaluation including core samples to determine which rehabilitation technique is required. The road segment will be grouped into one of two categories: microsurfacing or reconstruction. Microsurfacing will be performed as a preservation technique with the goal of postponing reconstruction. Reconstruction entails either expanded asphalt resurfacing or mill and overlay; the required reconstruction type is determined by the type, density and severity of the distresses present [Penner, 2012].

The generated road rehabilitation program is executed throughout the construction season; slight modifications to the program are made on an as needed basis. Modifications typically result due to budget constraints and escalated road deterioration due to water and hydro maintenance. The pavement condition data stored within the Hanson data base is updated post construction. The OCI of road segments not receiving rehabilitation is not updated; these road segments are only updated every two to three years when the entire road network is re-evaluated. Using the updated OCI data the City of Markham will begin to generate the road rehabilitation program for the next year [Penner, 2012].

It is recommended that pavement deterioration models be utilized to estimate the OCI of road segments not receiving rehabilitation. This will keep the pavement OCI data more accurate during the two to three years between road network evaluations. With more accurate OCI data, the City of Markham will be able to generate road rehabilitation programs better tailored to the road network needs; increasing the cost effectiveness of the road rehabilitation program.

5.4. Pavement Management System Review

A Pavement Management System (PMS) is a decision support tool used by pavement engineers and managers for the purposes of maintaining pavement networks at maximized levels of service. The role of a PMS in this project is to provide suggestions regarding maintenance and rehabilitation alternatives for road segments in need of maintenance. This section of the report provides an overview of MicroPAVER; a PMS tool that could potentially be used to incorporate sustainability into the City of Markham's network level decision making process.

5.4.1. Inventory and Field Data Collection

MicroPAVER allows users to input and store field data regarding the City's pavement network. The network is broken down into three levels which are network, branches and sections. A network consists of multiple branches and a branch in turn consists of multiple sections. When creating the database, the user must first define the various pavement networks. The next step is to break the networks down into branches which are defined as easily distinguishable pavement segments with a consistent use. The final step is to break the branches down into sections which are the smallest management units for maintenance and rehabilitation projects. These sections should have consistent characteristics throughout [APWA, 2011].

Collecting and updating the field data stored within MicroPAVER is recommended as a frequent routine. Field data can be collected on a computerized tablet, via paper forms or digitally and imported into MicroPAVER using the Condition Data Import feature [APWA, 2011].

5.4.2. Reports

The reports feature provides basic pavement information in a user friendly format; MicroPAVER provides five reporting tools which are displayed in Table 5.1.

Table 5.1 – MicroPAVER Reporting Tools [APWA, 2011]

Reporting Tool	Description
Summary Chart	Allows users to graph and compare any two pavement characteristics stored within the database
Standard Reports	These reports include: Branch Listing, Work History, Branch Condition and Section Condition Reports
Re-Inspection Reports	Provides a report containing information regarding each sections last inspection
User Defined Report	Allows users to create custom designed reports
GIS Reports	Provides users with preset arial views that displays a variety of database information

5.4.3. Prediction Modelling and Condition Analysis

The prediction modelling feature provides users with the ability to generate future condition models for all road sections stored within the MicroPAVER database. This is a very significant process since these models are used to analyse pavement conditions and in the generation of each pavement sections maintenance and rehabilitation requirements. Pavement sections with similar characteristics are grouped together into a "family". A single model is generated for each family and this model is used to predict the deterioration of each pavement section assigned to that family model [APWA, 2011].

The condition analysis feature examines the change in pavement condition for the selected pavement sections. The effects of past maintenance and rehabilitation projects can be evaluated through the comparison of past and present pavement conditions. Future pavement conditions are also predicted if no maintenance and rehabilitation is performed. These condition predictions can be used by decision makers when generating the annual pavement rehabilitation plan [APWA, 2011]

5.4.4. Maintenance and Rehabilitation Work Plan

The M&R Work Plan feature is a tool that assists users with the planning, scheduling and budgeting of the annual maintenance and rehabilitation activities. The generated work plan is configured to reflect the users site, pavement management practices and costs. MicroPAVER supports four work plan options which are: eliminate M&R backlog in x years, reach preferred area weighted PCI™ in x years, maintain current area weighted PCI™ and determining budget consequences [APWA, 2011]

5.5. Network Level Pavement Sustainability

This section of the report provides suggestions for improving the sustainability of the current City of Markham network level pavement management. The following three improvements are recommended:

1 Cost Effectiveness and Network Level GDLCC
2 Implementation of a PMS
3 Proactive Planning

5.5.1. Cost Effectiveness and Network Level GDLCC

The first recommendation to improve the sustainability of the City of Markham's network level pavement management is the utilization of Cost Effectiveness (CE) instead of OCI as the basis for generating the yearly road rehabilitation program. Cost effectiveness may be calculated through the following formula:

$$Cost\ Effectiveness\ (CE) = \frac{Effectiveness}{GDLCC\ x\ Segment\ Length\ (km)} \qquad \text{[Equation 5.1]}$$

Traditionally CE is calculated using LCC. However, using GDLCC instead of LCC incorporates the environmental aspect of sustainability; environmentally friendly alternatives receive larger green discounts than non-environmentally friendly alternatives and therefore become more appealing. Effectiveness is equal to the OCI gained by performing the treatment alternative in question. CE must be converted to a per kilometre value to be comparable with the CE values of other road segments.

The GDLCC formula displayed in section 4.4 may be slightly modified and adopted for network level pavement management. The project level GDLCC must be converted from Net Present Value (NPV) to an Equivalent Annual Worth (EAW) to be applicable on the network level. The purpose of converting the GDLCC into an EAW is for comparison purposes; treatments with different service lives can only be compared on an annual cost basis and not present worth. The following modification to the GDLCC formula is proposed: [Chan, 2010]

$$GDLCC = [LCCx(A/P, i, SL)]\ x\ [1 - Ax\left(\frac{GP}{32}\right)] \qquad \text{[Equation 5.2]}$$

Where:
LCC = Life Cycle Cost of the project in question
GP = GreenPave points awarded to the project in question
A = Discount factor controlling the sensitivity of the GDLCC, MTO suggests a value of 0.2
(A/P,i,SL) = Factor for converting NPV to EAW

The (A/P,i,SL) factor may be found in any statistics textbook or may be calculated manually using the following formula: [Chan, 2010].

$$(\mathrm{A/P, i, SL}) = \frac{\mathrm{i(1+i)^{SL}}}{\mathrm{(1+i)^{SL}-1}} \qquad \text{[Equation 5.3]}$$

Where:
i = Discount rate
SL= Predicted service life of the treatment in question

The objective of using CE instead of OCI is to maximize the effectiveness of budget allocation. Calculating CE provides decision makers with the ability to prioritize road segments with higher OCI gained to dollar spent ratios.

5.5.2. Implementation of a PMS

The most significant suggested improvement to the existing network level pavement management would be the implementation of a PMS. The adopted PMS will require customization to meet the needs and operations of the City of Markham. New decision trees will be required and potentially a new work plan scenario.

A new work plan scenario is proposed to increase the sustainability of the optimization process. The road network would be optimized based on the network level GDLCC; the alternative with the lowest network level GDLCC is selected. Optimizing based on the network level GDLCC would incorporate the environmental aspect while maintaining the economic; this incorporates a second aspect of sustainability into the generation of the optimal work plan.

A Pavement Management System is only a decision making support tool; the obtained results should be interpreted carefully and should only be used as a guide when making network level pavement management decisions.

5.5.3. Proactive Planning

A PMS plays a significant role in the proactive planning of pavement management because it provides suggestions for what, when and where rehabilitation is required. Therefore, it’s crucial that the collected field data, costing data and deterioration models within PMS are accurate. To maximize the potential benefits of a PMS, the following proactive planning recommendations are proposed: [Chan, 2010].

- Continuous update of pavement OCI data stored within the PMS (entire network evaluation every 2-3 years, update rehabilitated sections to 100 post construction, annual update of non-rehabilitated sections using deterioration models)
- Continuous calibration of deterioration models for existing treatment alternatives, and addition of deterioration models for new treatment alternatives
- Rehabilitation of road segments as close to the recommended year as possible to optimize benefits
- Routinely run maintenance and rehabilitation analysis on PMS during completion of yearly rehabilitation program and make necessary tweaks
- Allocate budget for future years based on the rehabilitation predictions made by the PMS

5.6. Development of Network Level Framework

The objective of a sustainable network level pavement management framework is to utilize the allocated budget in a manner that balances road network performance with environmental and social benefits. Given this objective, the proposed sustainable network level framework is displayed in Figure 5.2.

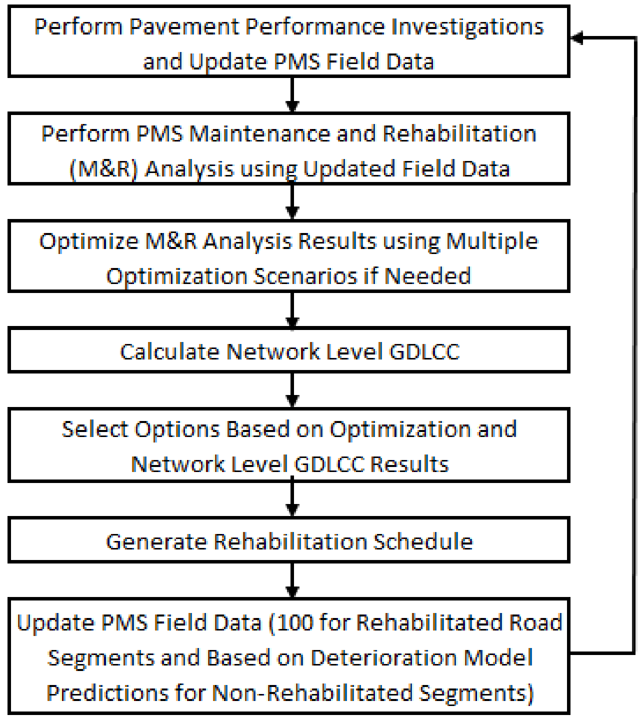


Figure 5.2 – Recommended Network Level Framework

The foundation of the proposed sustainable network level framework is the collection of accurate pavement performance data. Field data is used in the generation of the annual pavement rehabilitation program. Therefore with flawed field data, the rehabilitation program will be also be flawed which leads to the pavement network operating at less than maximum levels of service. The next step is to input the field data into a PMS and perform the maintenance and rehabilitation analysis. The results of this analysis must then be optimized using one or more of the available optimization scenarios; it is recommended that Cost Effectiveness (CE) be the basis of this optimization. Rehabilitation alternatives are then chosen using the optimization results and the network level GDLCC analysis results; this process generates the road rehabilitation program for the current year. The field data within the PMS must be updated annually, either increased to 100 post rehabilitation, updated based on deterioration models or a complete network update every two to three years. The final step is the proposition of a budget for the next year using the rehabilitation predictions made by PMS.

5.7. Network Level and Project Level Framework Connection

A sustainable pavement management operation requires the network and project levels to work together efficiently and effectively. Therefore, to assist the City of Markham in achieving pavement management sustainability, the following connections between the previously developed network level and project level frameworks are proposed. The connected frameworks are displayed in Figure 5.3.

The annual cycle begins at the top of the network level; following the network level framework steps, a road rehabilitation program is generated. This program specifies the road segments that require maintenance or rehabilitation for the current year. With the generation of this road rehabilitation program, the connected framework moves over to the project level. With the road segments in need of maintenance and rehabilitation identified at the network level, the project level attempts to select the optimal rehabilitation strategy for each of the identified road segments. By calculating the project level GDLCC and evaluating each project using GreenPave, its possible for decision makers to choose the most sustainable treatment alternatives. Following the completion of the current year's road rehabilitation program, the PMS field data must be updated to ensure the accuracy of next year's pavement management analysis. The current year's annual cycle is completed and the combined framework moves back to the top of the network level for next year's analysis.

To summarize, two connections between the network and project level frameworks are proposed. The first connection occurs from the network level to the project level once the road rehabilitation program has been generated. The second and most crucial connection occurs from the project level to the network level post construction; the PMS field data must be updated to ensure the accuracy of next year's pavement management analysis.

5.8. Chapter 5 Summary

This chapter focuses on the development of a framework for incorporating sustainability into the project level and network level pavement management practices at the City of Markham. Once the need for maintenance at a specific road segment is identified, the project level framework is used to determine the optimal rehabilitation strategy for that segment. The project level framework is centred on GreenPave.

To aid in the development of a network level framework, the City of Markham's current network level practices are reviewed. MicroPAVER is also reviewed as a potential Pavement Management System for the City of Markham. MicroPAVER would be used for aiding decision makers in generating the annual pavement rehabilitation plan. Three recommendations are made that will improve the sustainability of the City of Markham's network level pavement management. These three recommendations are network level GDLCC, implementation of a PMS and proactive planning. The recommended network level framework is developed and then the project level and network level frameworks are connected.

The proposed project level framework builds on existing practices through the calculation of the GDLCC and the GreenPave score of all rehabilitation alternatives and using these indicators in addition to detailed field investigations when making decisions. Additional costs to current practices are incurred due to extra hours of work and employee training.

The proposed network level framework is similar to current City of Markham practices with one key difference, which is the method in which the annual road rehabilitation work plan is generated. Currently the City of Markham generates its road rehabilitation work plan manually through engineering judgement; while the new system proposes that a PMS serve as a platform when generating the work plan. Operating costs of the proposed network level framework would not change significantly when compared to the operating costs of the current method. There is a potential for cost savings since the work plan is generated faster therefore requiring less hours of labour. Start up costs include the purchasing cost of the chosen PMS and employee training.

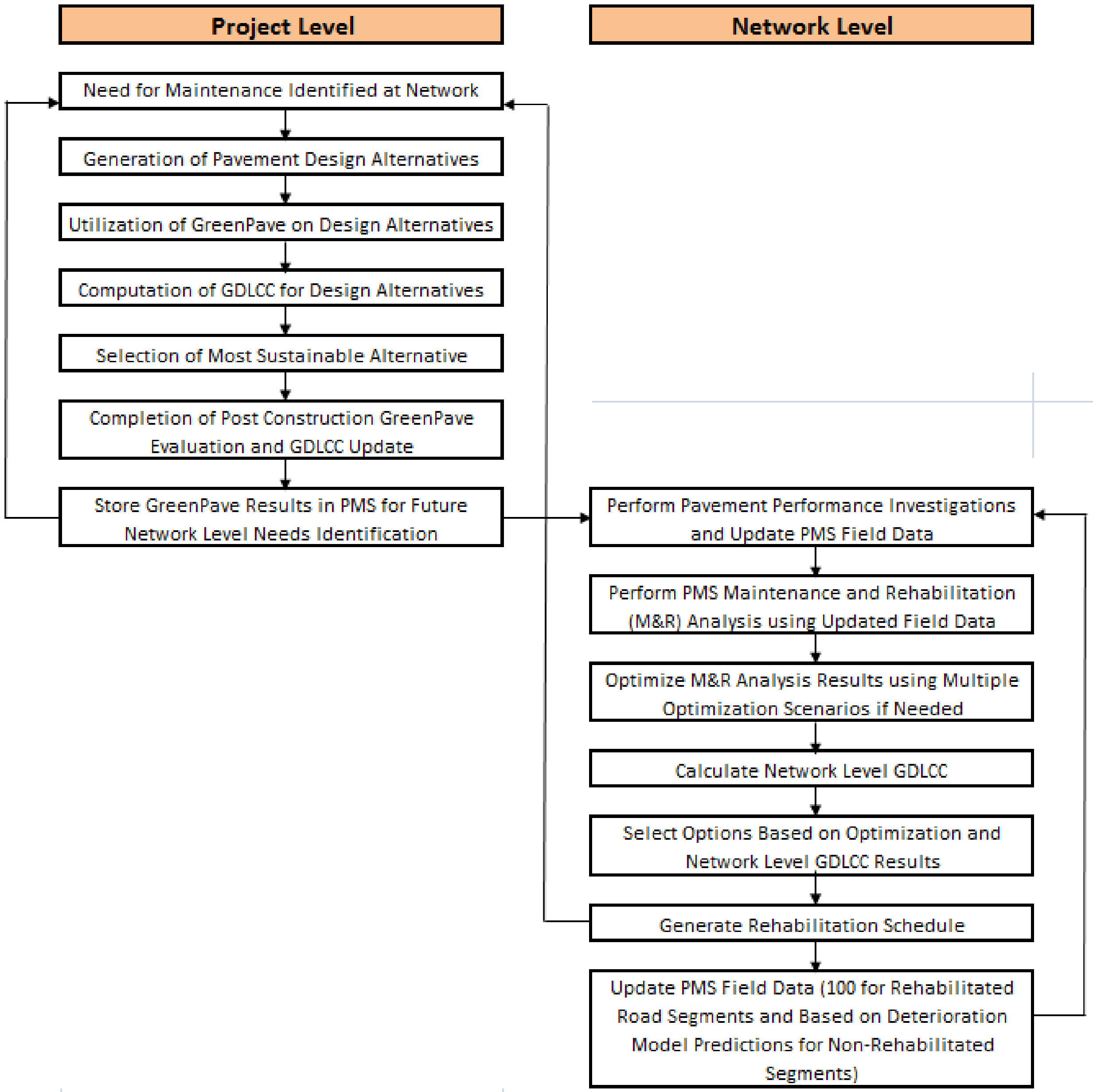


Figure 5.3 – Connection between Network Level and Project Level Frameworks

Chapter 6
ANALYSIS GUIDELINES

6.1. Introduction

The objective of this chapter is to develop guidelines and recommendations for the usage of sustainable pavement best practices by the City of Markham based on the results of chapter 4 and chapter 5. Three indicators to promote sustainability in the project and network level pavement management decision making processes were recommended; these indicators were project level GDLCC, network level GDLCC and cost effectiveness. The objective is to provide the City of Markham with guidelines on the computation of these three indicators through numerical examples. The results of the hypothetical examples are discussed.

6.2. Project Level GDLCC

This section of the report presents a solved numerical example for the project level GDLCC indicator. Consider the data provided in Table 6.1.

Table 6.1 – Project Level GDLCC Data

Alternative	Construction Type	LCC	GreenPave
1	Hot Mix Asphalt	$ 257,037.00	9
2	HMA with RAP	$ 239,564.00	9.9

Alternative	Rehabilitation Type	LCC	GreenPave
1	Mill and Overlay with RAP	$ 243,963.00	9.4
2	CIP	$ 130,033.00	16
3	CIREAM	$ 168,325.00	16

GDLCC is computed for both construction alternatives and all three rehabilitation alternatives using the project level GDLCC equation proposed in section 4.4.

New Construction

Alternative 1

GDLCC = LCC – LCC x A x (GP/32)

GDLCC = $257037 – 257037(0.2)(9/32)

GDLCC = **$242578.67**

Alternative 2

GDLCC = $239564 – $239564(0.2)(9.9/32)

GDLCC = **$224740.98**

The results indicate that HMA with RAP has a lower GDLCC than traditional HMA; therefore HMA with Rap is the more sustainable alternative for this project.

Rehabilitation

Alternative 1

GDLCC = LCC – LCC x A x (GP/32)

GDLCC = $243963 – 243963(0.2)(9.4/32)

GDLCC = **$229630.17**

Alternative 2

GDLCC = $130033 – $130033(0.2)(16/32)

GDLCC = **$117029.70**

Alternative 3

GDLCC = $168325 – $168325(0.2)(16/32)

GDLCC = **$151492.50**

The results indicate that CIP has the lowest GDLCC followed by CIREAM and then Mill and Overlay with RAP; therefore CIP is the most sustainable alternative for this project.

6.3. Network Level GDLCC

This section of the report presents a solved numerical example for the network level GDLCC indicator. Consider the data provided in Table 6.2 assuming a discount rate of 6% is used.

Table 6.2 – Network Level GDLCC Data

Road Segment	Estimated LCC	Service Life	GreenPave
1	$ 197,254.00	10	11.5
3	$ 263,782.00	17	22
2	$ 231,784.00	14	9
4	$ 254,265.00	15	16

Network level GDLCC is computed for four road segments using the equation proposed in section 5.5.1.

$$GDLCC = [LCCx(A/P, i, SL)]\ x\ [1 - Ax\left(\frac{GP}{32}\right)]$$

$$(\mathrm{A/P, i, SL}) = \frac{\mathrm{i(1+i)^{SL}}}{\mathrm{(1+i)^{SL}-1}}$$

Road Segment 1

$$(\mathrm{A/P, i, SL}) = \frac{0.06(1+0.06)^{10}}{(1+0.06)^{10}-1} = 0.1359$$

GDLCC = $197254(0.1359)[1 – 0.2(11.5/32)] = **$24880.08**

Road Segment 2

$$(\mathrm{A/P, i, SL}) = \frac{0.06(1+0.06)^{17}}{(1+0.06)^{17}-1} = 0.0954$$

GDLCC = $263782(0.0954)[1 – 0.2(22/32)] = **$21704.64**

Road Segment 3

$$(\mathrm{A/P, i, SL}) = \frac{0.06(1+0.06)^{14}}{(1+0.06)^{14}-1} = 0.1076$$

GDLCC = $231784(0.1076)[1 – 0.2(9/32)] = **$23537.09**

Road Segment 4

$$(\mathrm{A/P, i, SL}) = \frac{0.06(1+0.06)^{15}}{(1+0.06)^{15}-1} = 0.1030$$

GDLCC = $254265(0.1030)[1 – 0.2(16/32)] = **$23570.37**

From the above calculations, road segment 2 has the lowest network level GDLCC of the four road segments even though it has the highest cost. Road segment 2 has the highest GreenPave score and longest life span; these two characteristics allow it to be the most sustainable rehabilitation choice.

6.4. Cost Effectiveness

This section of the report presents a solved numerical example for the cost effectiveness indicator. Consider the data provided in Table 6.3; the road segments and their corresponding network level GDLCC values were continued from the previous section.

Table 6.3 – Cost Effectiveness Data

Road Segment	Existing OCI	Network Level GDLCC	Segment Length (km)
1	54	24880.08	1.2
2	56	21704.64	1.4
3	62	23537.09	1.8
4	59	23570.37	2.2

$$Cost\ Effectiveness\ (CE) = \frac{Effectiveness}{GDLCC\ x\ Segment\ Length\ (km)}$$

Road Segment 1

$$CE = \frac{100-54}{24880.08\ x\ 1.2} = \mathbf{0.00154}\ \frac{OCI\ Gained}{\$km}$$

Road Segment 2

$$CE = \frac{100-56}{21704.64\ x\ 1.4} = \mathbf{0.00145}\ \frac{OCI\ Gained}{\$km}$$

Road Segment 3

$$CE = \frac{100 - 62}{23537.09\ x\ 1.8} = \mathbf{0.00090}\ \frac{OCI\ Gained}{\$km}$$

Road Segment 4

$$CE = \frac{100 - 59}{23570.37\ x\ 2.2} = \mathbf{0.00079}\ \frac{OCI\ Gained}{\$km}$$

From the above calculations road segment 1 has the highest cost effectiveness with road segment 2 a close second; therefore based on cost effectiveness road segment 1 would be the most sustainable choice.

The network level decision makers would use the results of the network level GDLCC and cost effectiveness calculations in deciding which road segments will be rehabilitated in the yearly road rehabilitation program. In addition to these two indicators, decision makers should consider the social impacts at each road segment and available budget when generating the rehabilitation program.

Once a road segment has been chosen, possible rehabilitation techniques for the road segment should be generated and designed. The project level GDLCC indicator will aid decision makers in identifying the most sustainable rehabilitation technique for each individual road segment.

Chapter 7
CONCLUSIONS AND RECOMMENDATIONS

Transportation infrastructure continuously deteriorates over time; therefore there is a continuous need for maintenance. Maintaining a functioning road network is a challenge in today's society due to limited financial and resource availability. In addition, the concept of sustainability is rapidly gaining momentum; pressuring transportation agencies such as the City of Markham to find cost effective, environmentally friendly and socially acceptable solutions. A means of determining how to effectively and efficiently spend limited funding must be found. This project entitled "Quantifying Pavement Sustainability" demonstrates the City of Markham's dedication to incorporating sustainability into their pavement engineering operations.

This thesis presents a practical framework for incorporating pavement sustainability best practices into the pavement engineering operations at the City of Markham; both project level and network level frameworks are considered.

Framework development initially began with the completion of a comprehensive literature review, where all state-of-the-art pavement engineering best practices are reviewed. The best practices are grouped into four categories which are materials, design and construction techniques and maintenance and rehabilitation techniques and carbon footprinting. A fifth category was created for sustainability evaluation systems. These evaluation systems provide a numerical value for the level of sustainability pavement projects achieve; the GreenPave rating system is chosen as the recommended sustainability evaluation system.

The costs provided in these conclusions are for the local road classification; however the same conclusions can be made for all other classifications. The pavement construction and maintenance best practices identified in the literature review were then analysed using PaLATE to determine the environmental, economic and greenhouse impacts of each technology. The PaLATE results indicate that warm mix asphalt and full depth reclamation are the most environmentally friendly construction and rehabilitation techniques, respectively. Including RAP within pavement mix designs reduces both costs and environmental impacts. Excluding microsurfacing, full depth reclamation was the least expensive rehabilitation technique (EAW of $3,797.27) while hot mix asphalt with RAP was the cheapest construction technique (EAW of $15,970.93). The most expensive initial construction and rehabilitation techniques are pervious concrete (EAW of $37,211.65) and mill and overlay (EAW of $23,691.18), respectively

The same initial construction and rehabilitation techniques are evaluated using the GreenPave rating system. Pervious concrete (11 points) scored the highest rating under the initial construction category with warm mix asphalt (10.4 points) a close second. Cold in place recycling, cold in place with expanded asphalt and full depth reclamation all scored 16 points which was the highest under the rehabilitation category. In the future, the City of Markham may wish to alter the GreenPave rating system to be more reflective of municipal practices as it is recognized the current GreenPave system may be weighted more heavily on high volume roads. GreenPave only evaluates the environmental aspect of sustainability. Therefore, to include the economical aspect, the green discounted life cycle cost (GDLCC) is calculated for all techniques. The GDLCC reduces the project's life cycle cost based on the level of sustainability achieved under the GreenPave rating system. Hot mix asphalt with RAP (GDLCC of $224,740.98) and full depth reclamation (GDLCC of $27,747.91) resulted with the lowest GDLCC in the initial construction and rehabilitation categories, respectively.

Finally, the recommended project and network level frameworks for incorporating sustainability into the pavement engineering practices at the City of Markham are proposed. On the project level, GreenPave evaluation and project level GDLCC aid decision makers in determining the most sustainable project alternative. On the network level, a pavement management system (PMS) serves as the platform. The role of a PMS is to provide recommendations on when and where rehabilitation is required and which rehabilitation technique is the most sustainable. Cost effectiveness and network level GDLCC indicators also aid pavement engineers in making network level decisions. The project and network level frameworks are then connected to provide a complete pavement management framework for incorporating sustainability.

The City of Markham is committed to incorporating sustainability into their daily pavement engineering operations; the objective of this project is to propose a practical framework that will assist the City of Markham in fulfilling this commitment. Through the completion of this project, project and network level frameworks are developed. The City of Markham's next step is to move forward and make sustainability promoting modifications to their current pavement management practices. The incorporation of a Pavement Management System and GreenPave is highly recommended. With the completion of these modifications, a project evaluating the effectiveness of said modifications is recommended to be completed. The results of this project will indicate whether or not credible results were achieved through the incorporation of the proposed frameworks and whether or not addition modifications are necessary.

The City of Markham is recommended to modify the current version of GreenPave before incorporating it into their pavement engineering operations as it is currently tailored towards the high volume roads of the MTO road network. These modifications will allow City of Markham projects to achieve higher levels of GreenPave certification which will better reflect their levels of sustainability. These modifications involve adjustments to the GreenPave criteria to ensure they are suited to the lower volume roads of the City of Markham road network. For example: including pavements designed with service lives of over 30 years to the long-life pavements criterion.

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Appendix A
PaLATE Walkthrough

Introduction

Appendix A provides new users with an explanation regarding how PaLATE is used to quantify the costs and environmental impacts of pavement projects. PaLATE was developed by a research team lead by Dr. Arpad Horvath at the University of California, Berkley. The program is an input/output excel based tool used for quantifying the environmental and economical impacts of pavement projects. For the purposes of this report, PaLATE was used to quantify both economical costs and environmental savings, therefore a full walkthrough of the program is provided.

The PaLATE excel workbook contains multiple work sheets falling under three categories: input, output and data. The first worksheet labeled “Intro” does not fall under any of these categories and is meant to provide the user with a short guide. The input section contains five worksheets which are: Design, Initial Construction, Maintenance, Equipment and Cost. The user is allowed to enter data regarding pavement dimensions, material volumes, transportation distances and modes, processes, costs and equipment in these worksheets. The output section contains two worksheets which are cost results and environmental results. These worksheets provide the user with the results of the economical and environmental analysis in the form of tables and plots. The data section contains eight worksheets which are: densities, equipment details, EMF Transport, Fumes, Leachate, Cost Data, Conversions and Diagram. These worksheets contain the data used to analyze the provided input and produce the output. The information contained within these slides is not intended to be modified under normal circumstances. The next sections provide an in depth look at the following worksheets: Design, Initial Construction, Maintenance, Cost, Economical Results and Environmental Results.

Design Worksheet

This section of the report presents a walkthrough of the Design worksheet. The Design worksheet requires the user to input information regarding pavement dimensions and material densities. The first table requires the user to input the dimensions (width, length and depth) of each pavement layer. PaLATE can accommodate up to 7 layers, 3 wearing course and 4 subbase layers. If the pavement design contains a shoulder or embankment, the volume can be entered under the pavement dimension table. Typical City of Markham roads do not have shoulders or embankments. The analysis period up to a maximum of 40 years may be entered under the shoulder/embankment volume cell. The remaining two tables contains the material and process densities. Default values are included; however they may be changed if inconsistencies between these values and the design densities exist. The default density values were used. Figure B.1 displays the layout of the design worksheet.

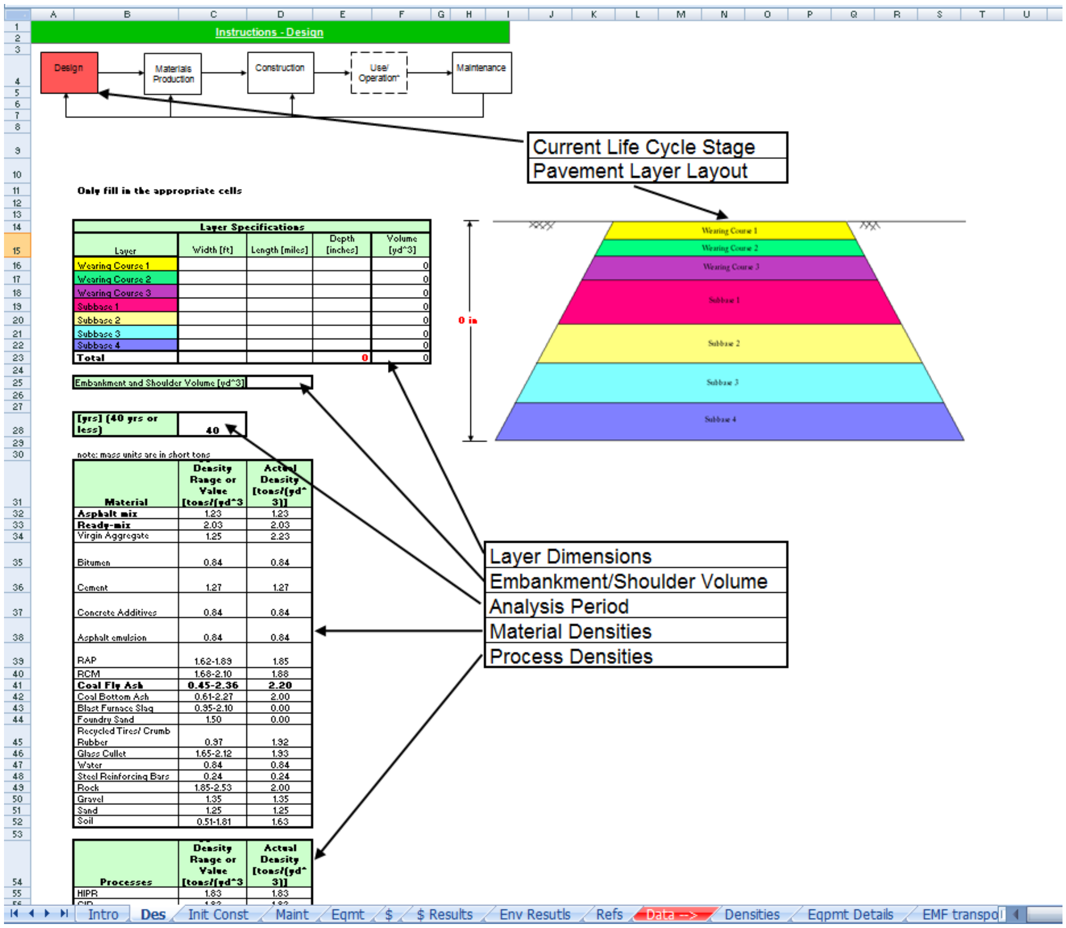


Figure B.1 – Design Worksheet Layout

Initial Construction Worksheet

The initial construction worksheet allows users to input data regarding the materials used in each pavement layer. The user must specify the volume, transportation distance and transportation mode associated with each material. PaLATE lists a wide range of possible materials that may be included within asphalt or concrete pavements; materials not included within the design may be disregarded. This worksheet is organized into the same three wearing course and four subbase layers as the Design worksheet. The layer designations in the Design and Initial Construction worksheets must match. Figure B.2 displays the Initial Construction worksheet layout. Data must not be entered into the grey cells.

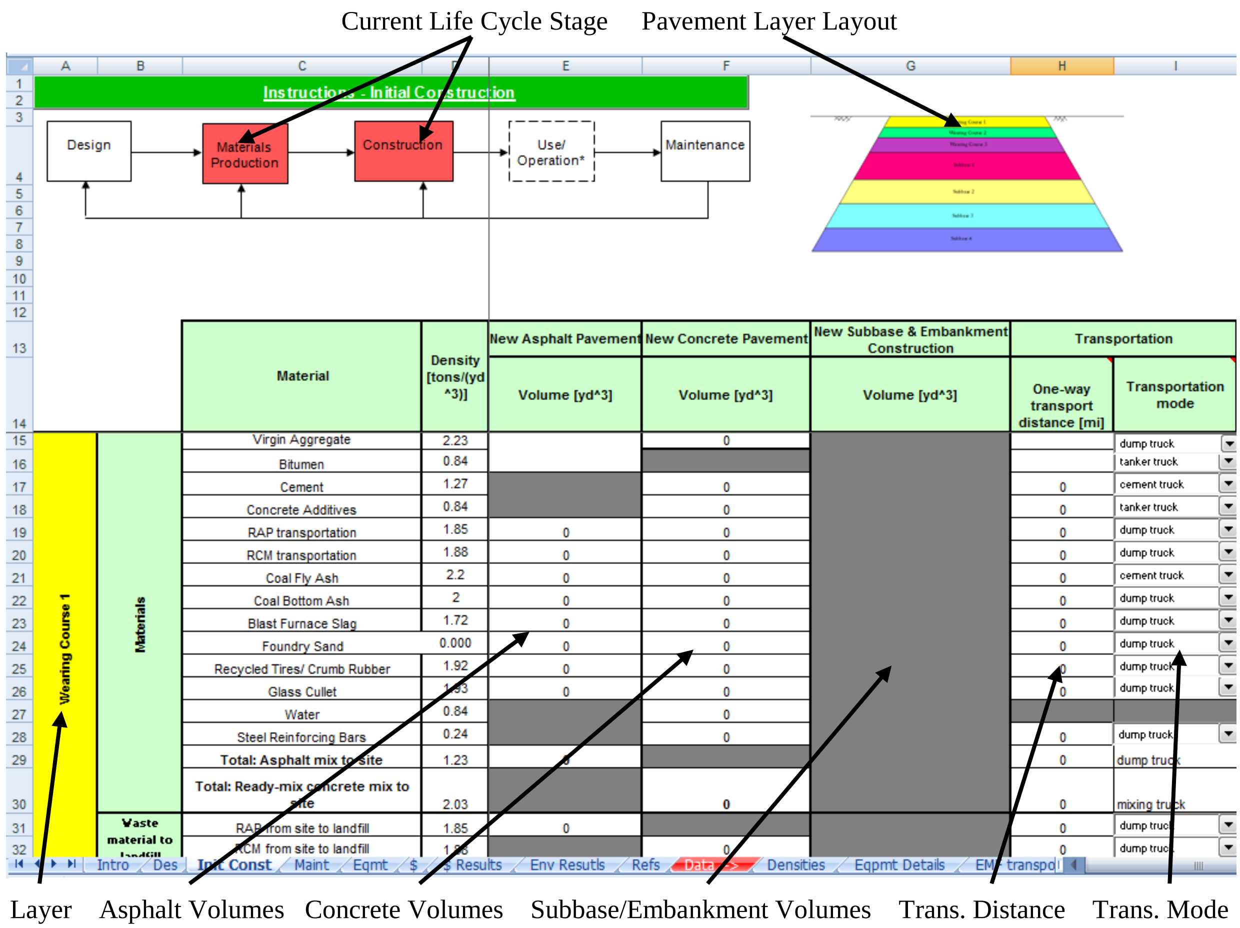


Figure B.2 – Initial Construction Worksheet Layout

Maintenance Worksheet

The Maintenance worksheet allows the user to input data regarding the maintenance and rehabilitation processes performed on pavements. Data within this worksheet is grouped into two categories which are materials and processes. The user must input material volumes, transportation distances and transportation modes into the material section. The processes section allows users to incorporate maintenance and rehabilitation techniques into the analysis by entering the lifetime asphalt/concrete volumes used. The processes PaLATE can analyze are Hot In-Place Recycling, Cold In-Place Recycling, Patching, Microsurfacing, Crack Sealing, Whitetopping, Rubblization and Full Depth Reclamation. Figure B.3 displays the Maintenance worksheet layout; the differences between the Initial Construction and Maintenance worksheets are highlighted.

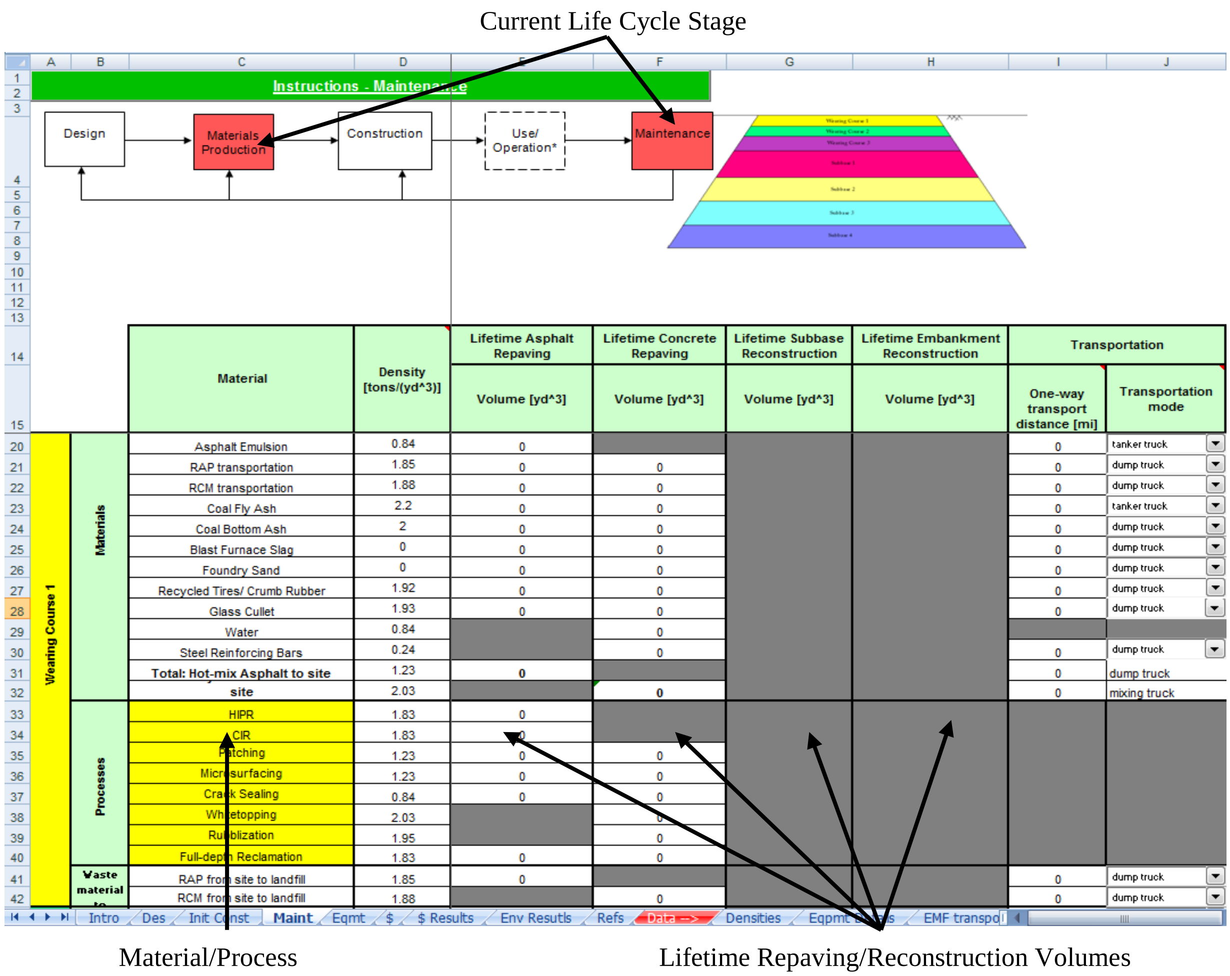
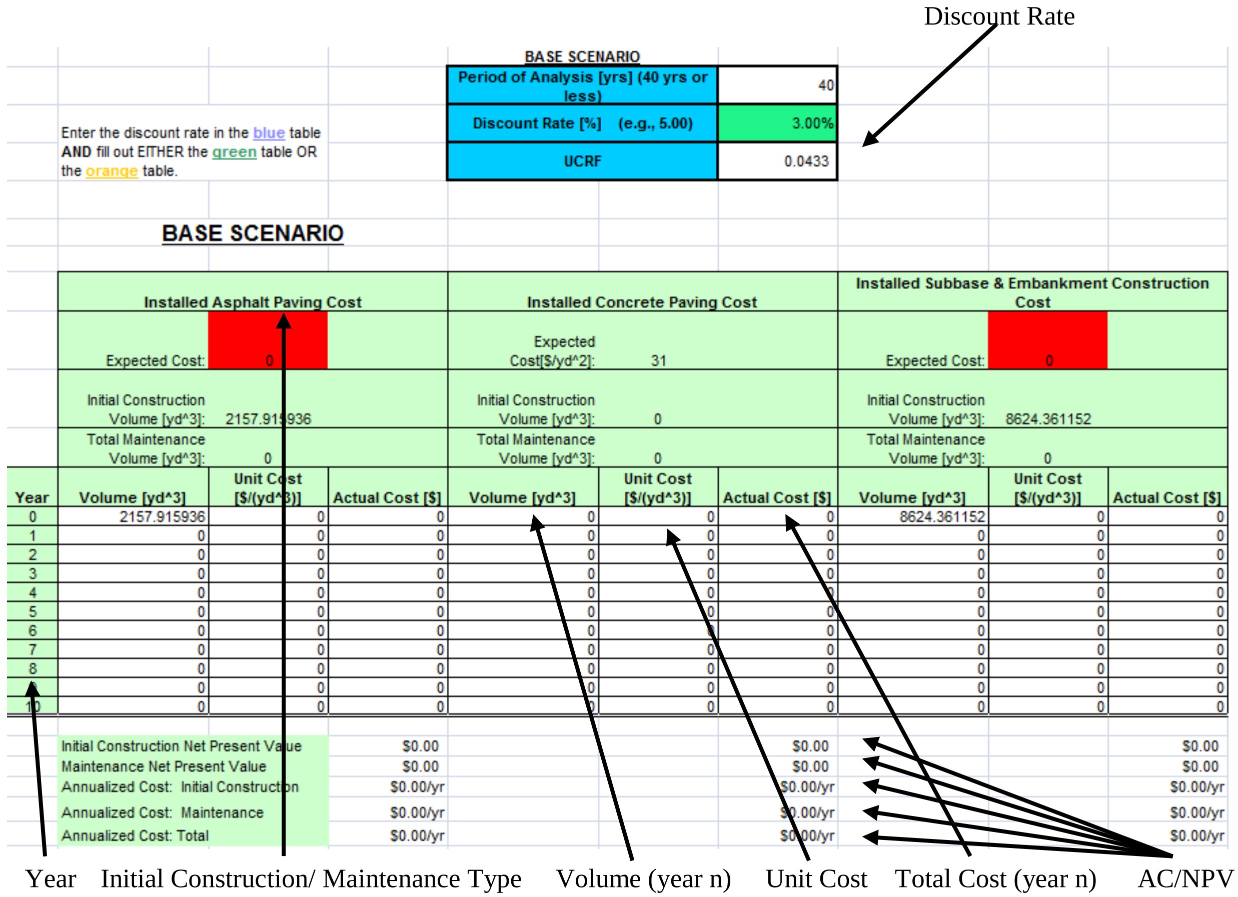


Figure B.3 – Maintenance Worksheet Layout

Cost Worksheet

The Cost worksheet allows users to input data regarding project expenditures. PaLATE allows the user to input expenditure data in either the lump sum format (a single cost is required for each construction or maintenance technique) or in unit cost format (individual material costs, labour costs, equipment costs and profit margins are required). The user must specify the analysis period and discount rate regardless of the chosen format. PaLATE also allows the user to compare two alternative pavement proposals; alternative 1 is labeled “Base Scenario” while alternative 2 is labeled “Alternative Scenario”. This feature allows users to make informed decisions when faced with a decision between two competing pavement proposals.

Figure B.4 displays the layout of the lump sum format. The user must input the construction volume and lump unit cost ($/yard^3) for each construction and maintenance technique. PaLATE provides the Net Present Values (NPV) and annualized costs for the specified pavement construction and maintenance techniques.



BASE SCENARIO

Period of Analysis [yrs] (40 yrs or less)	40
Discount Rate [%] (e.g., 5.00)	3.00%
UCRF	0.0433

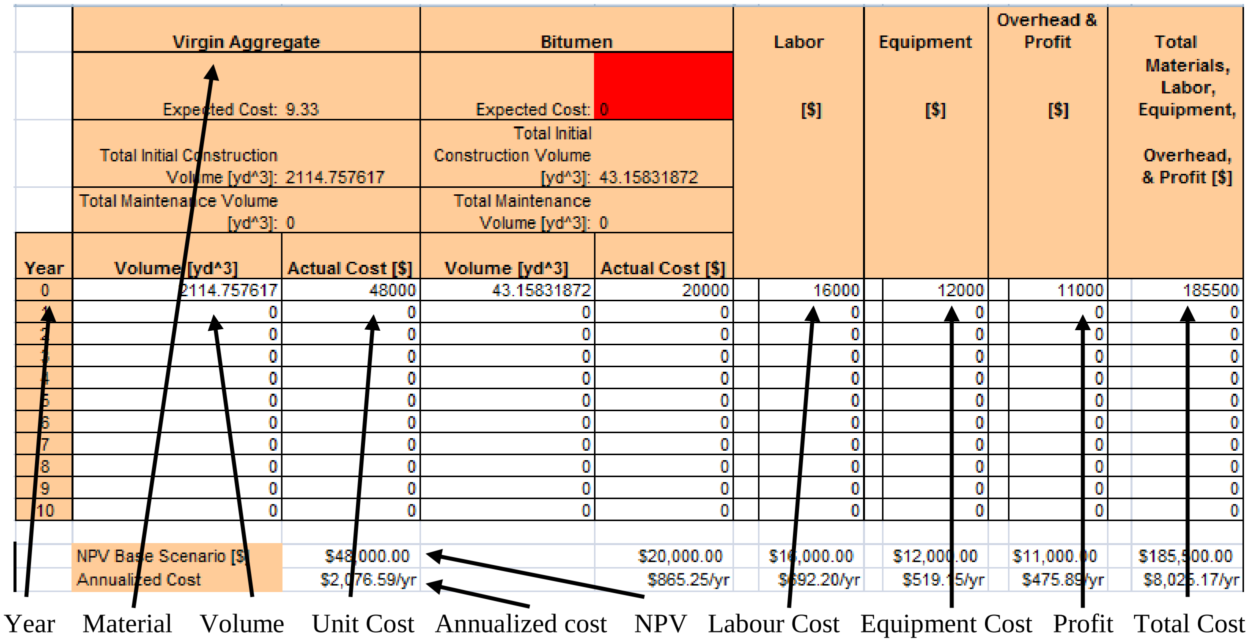
Enter the discount rate in the blue table AND fill out EITHER the green table OR the orange table.

BASE SCENARIO

	Installed Asphalt Paving Cost			Installed Concrete Paving Cost			Installed Subbase & Embankment Construction Cost		
	Expected Cost:	0		Expected Cost[$/yd^2]:	31		Expected Cost:	0	
	Initial Construction Volume [yd^3]:	2157.915936		Initial Construction Volume [yd^3]:	0		Initial Construction Volume [yd^3]:	8624.361152	
	Total Maintenance Volume [yd^3]:	0		Total Maintenance Volume [yd^3]:	0		Total Maintenance Volume [yd^3]:	0	
Year	Volume [yd^3]	Unit Cost [$/(yd^3)]	Actual Cost [$]	Volume [yd^3]	Unit Cost [$/(yd^3)]	Actual Cost [$]	Volume [yd^3]	Unit Cost [$/(yd^3)]	Actual Cost [$]
0	2157.915936	0	0	0	0	0	8624.361152	0	0
1	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0
	Initial Construction Net Present Value		$0.00			$0.00			$0.00
	Maintenance Net Present Value		$0.00			$0.00			$0.00
	Annualized Cost: Initial Construction		$0.00/yr			$0.00/yr			$0.00/yr
	Annualized Cost: Maintenance		$0.00/yr			$0.00/yr			$0.00/yr
	Annualized Cost: Total		$0.00/yr			$0.00/yr			$0.00/yr

Figure B.4 – Cost Worksheet Layout (Lump Sum)

Figure B.5 displays the layout of the unit cost format. The unit cost format allows the user to input material costs and volumes on an individual material basis. In addition to material costs and volumes, the user must input labour costs, equipment costs and the expected profit margin. PaLATE provides the NPV and annualized costs for the specified materials.



	Virgin Aggregate		Bitumen		Labor	Equipment	Overhead & Profit	Total Materials, Labor, Equipment, Overhead, & Profit [$]
	Expected Cost: 9.33		Expected Cost: 0		[$]	[$]	[$]	
	Total Initial Construction Volume [yd^3]: 2114.757617		Total Initial Construction Volume [yd^3]: 43.15831872					
	Total Maintenance Volume [yd^3]: 0		Total Maintenance Volume [yd^3]: 0					
Year	Volume [yd^3]	Actual Cost [$]	Volume [yd^3]	Actual Cost [$]				
0	2114.757617	48000	43.15831872	20000	16000	12000	11000	185500
1	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0
	NPV Base Scenario [$]	$48,000.00		$20,000.00	$16,000.00	$12,000.00	$11,000.00	$185,500.00
	Annualized Cost	$2,076.59/yr		$865.25/yr	$692.20/yr	$519.15/yr	$475.89/yr	$8,025.17/yr

Figure B.5 – Cost Worksheet Layout (Unit Cost)

Cost Results Worksheet

The Cost Results worksheet summarizes the economical life cycle analysis results. The results are displayed graphically in four figures which are:

- Net Present Value Life-Cycle Costs Broken Down by Phase (Figure B.6)
- Net Present Value Life-Cycle Costs Broken down by Materials and Processes (Figure B.7)
- Annualized Costs: Net Present Value Life-Cycle Costs Broken Down by Phase (Figure B.8)
- Annualized Costs: Net Present Value Life-cycle Costs Broken down by Materials and Processes (Figure B.9)

These figures provide a comparison between alternative 1 and alternative 2. In the displayed hypothetical case, alternative 1 resulted with a higher NPV life-cycle cost than alternative 2; therefore alternative 2 is the preferred option.

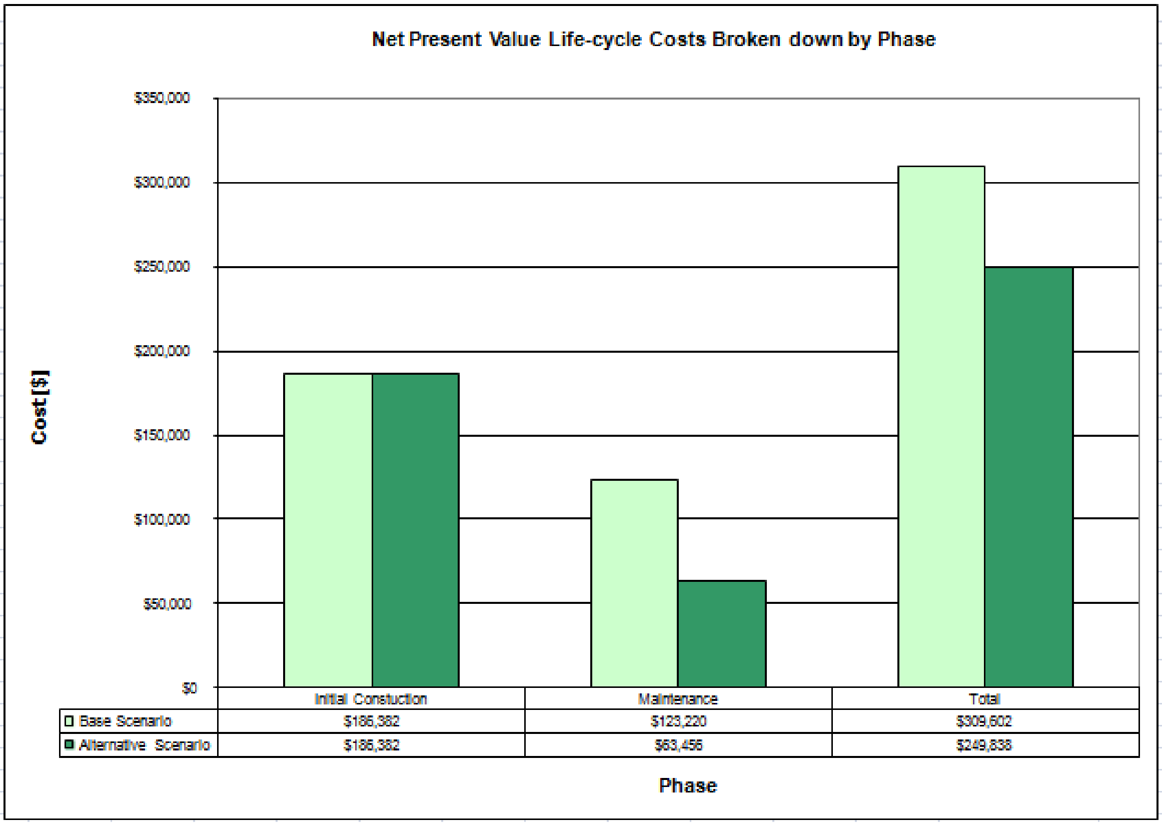


Figure B.6 – Sample Cost Worksheet Output

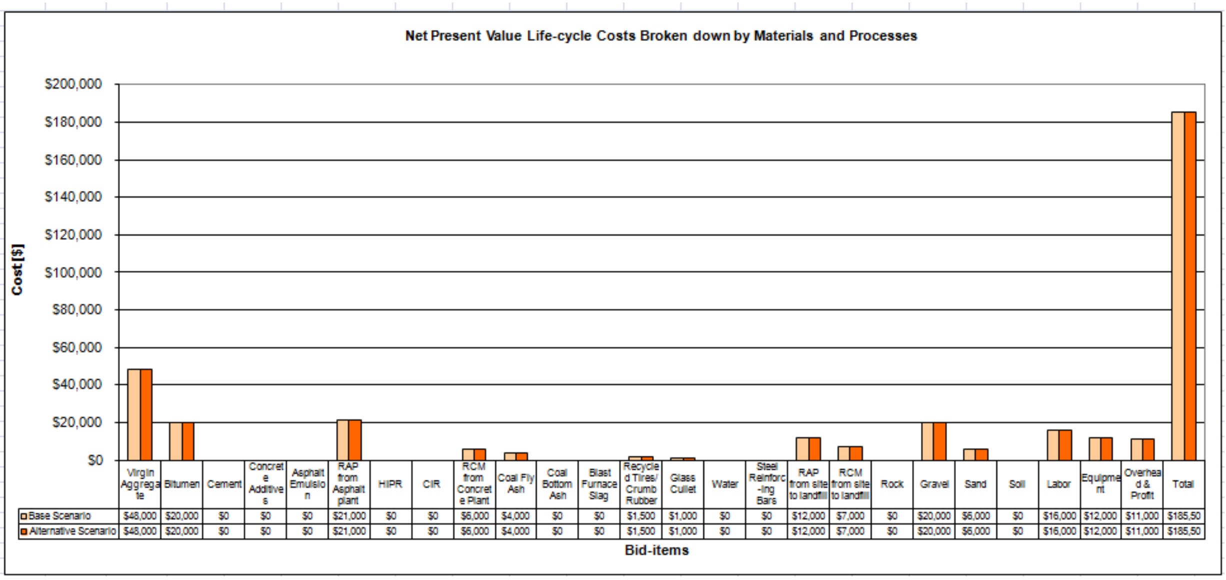


Figure B.7 – Sample Cost Worksheet Output

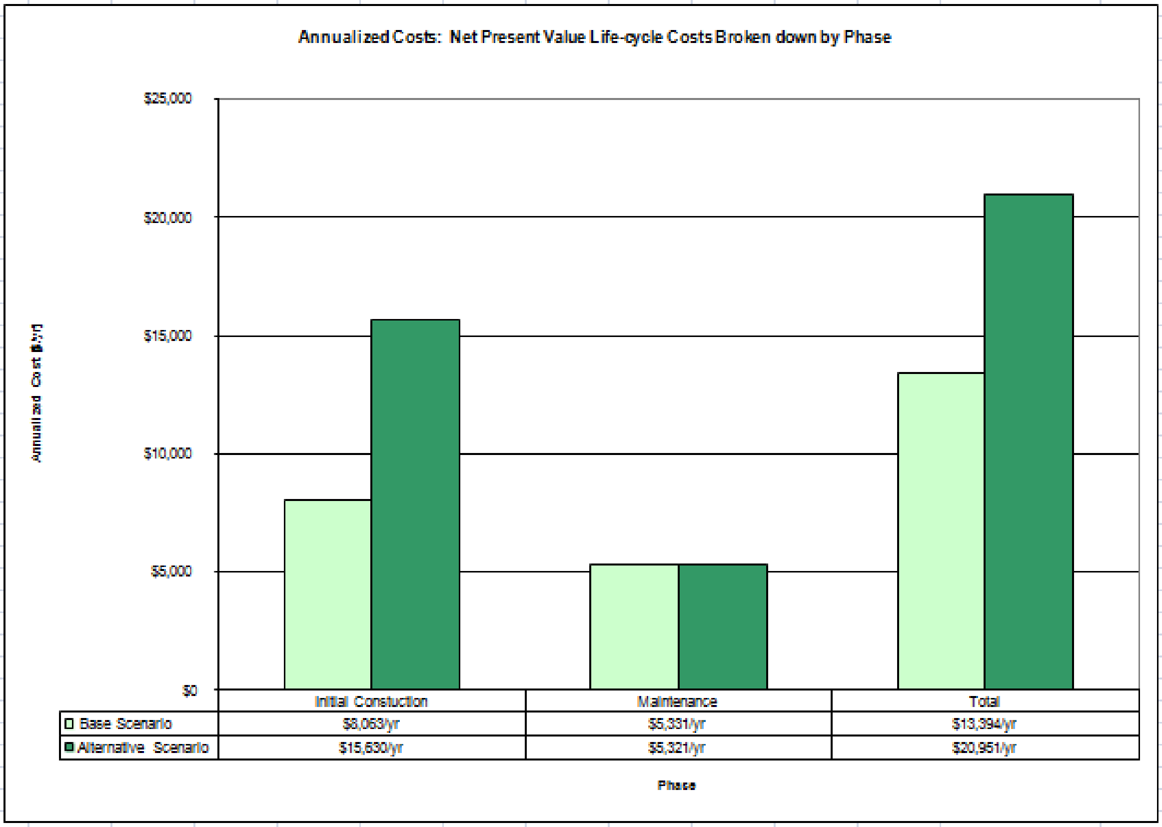


Figure B.8 – Sample Cost Worksheet Output

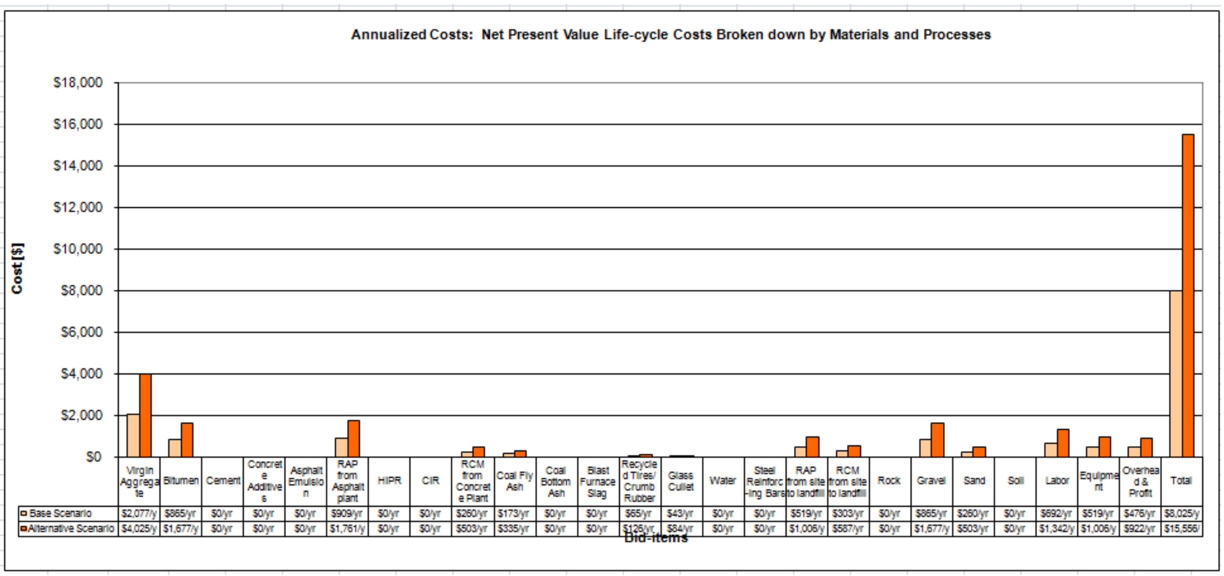


Figure B.9 – Sample Cost Worksheet Output

Environmental Results Worksheet

The Environmental Results worksheet summarizes the environmental life cycle analysis results. The results are displayed in tabular format and graphically. Table B.**1** displays a sample of the environmental LCA tabular results. A maintenance technique was analyzed in this example;

therefore the initial construction section contains no emissions. Figure B.10 displays sample bar chart of the life cycle energy consumption criterion. The figure displays the energy consumption criterion only; similar bar charts are produced for all criteria which are displayed as columns in Table B.**1**.

Table B.1 – Sample Environmental LCA Results

		Energy [MJ]	Water Consumption [kg]	CO_2 [Mg] = GWP	NO_x [kg]	PM_{10} [kg]	SO_2 [kg]	CO [kg]	Hg [g]	Pb [g]	RCRA Hazardous Waste Generated [kg]	Human Toxicity Potential (Cancer)	Human Toxicity Potential (Non-cancer)
Initial Construction	Materials Production	0	0	0	0	0	0	0	0.00	0	0	0	0
	Materials Transportation	0	0	0	0	0	0	0	0.00	0	0	0	0
	Processes (Equipment)	0	0	0	0	0	0	0	0.00	0	0	0	0
Maintenance	Materials Production	733,233	198	37	273	197	10,978	115	1	38	7,570	130,434	205,876,896
	Materials Transportation	25,667	4	2	102	21	6	9	0	1	185	550	675,003
	Processes (Equipment)	4,029	0	0	7	1	0	2	0	0	0	0	0
Total	Materials Production	733,233	198	37	273	197	10,978	115	0.74	38	7,570	130,434	205,876,896
	Materials Transportation	25,667	4	2	102	21	6	9	0.02	1	185	550	675,003
	Processes (Equipment)	4,029	0	0	7	1	0	2	0.00	0	0	0	0
	Total	**762,930**	**203**	**39**	**382**	**218**	**10,985**	**126**	**0.76**	**39**	**7,754**	**130,984**	**206,551,899**

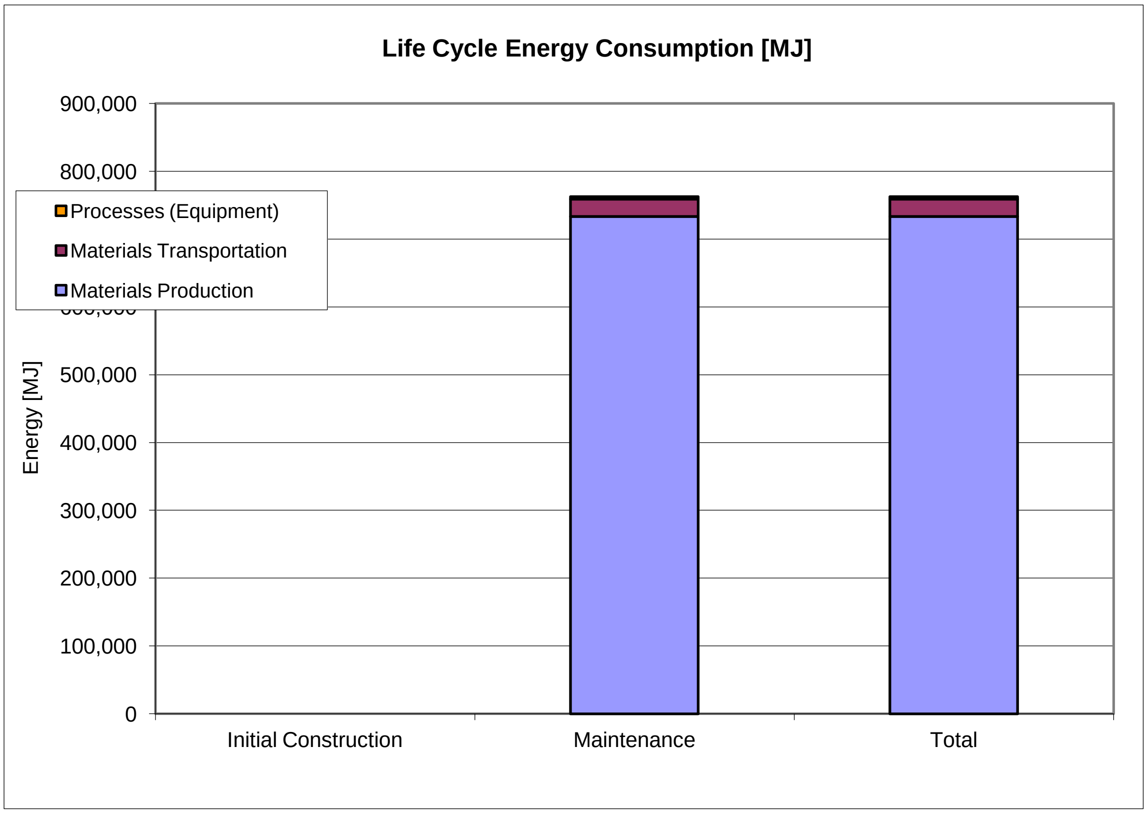


Figure B.10 – Sample Environmental LCA Bar Chart Result

Appendix B
PaLATE Input

INPUT – Initial Construction

Table C.1 – Initial Construction PaLATE Input (Industrial)

Process	Initial or Maint.	Layer	Material	Percent	Layer Depth	Width (m)
HMA	Initial	Wearing Course 1 (Superpave 12.5)	Virgin Aggregate	95	50	13.0
			Bitumen	5		
		Wearing Course 2 (Super Pave 19.0)	Virgin Aggregate	95	100	
			Bitumen	5		
		Subbase 1 (Granular A)	RAP to Site	30	150	
			Gravel to site	70		
		Subbase 2 (Granular B)	RAP to site	30	450	
			Rock to Site	70		
Porous Asphalt	Initial	Wearing Course 1	Virgin Aggregate	93	150	
			Bitumen	7		
		Subbase 1 (Drainage layer)	Rock to Site	100	600	
Asphalt with 20%/15% RAP	Initial	Wearing Course 1 (Superpave 12.5)	Virgin Aggregate	80.75	50	
			RAP	14.25		
			Bitumen	5		
		Wearing Course 2 (Superpave 19.0)	Virgin Aggregate	76	100	
			RAP	19		
			Bitumen	5		
		Subbase 1 (Granular A)	RAP to site	30	150	
			Gravel to site	70		
		Subbase 2 (Granular B)	RAP to site	30	450	
			Rock to Site	70		
Asphalt with 3% RAS	Initial	Wearing Course 1 (Superpave 12.5)	Virgin Aggregate	95	50	
			Bitumen	4		
			RAS	1		
		Wearing Course 2 (Superpave 19.0)	Virgin Aggregate	95	100	
			Bitumen	4		
			RAS	1		
		Subbase 1 (Granular A)	RAP to site	30	150	
			Gravel to site	70		
		Subbase 2 (Granular B)	RAP to site	30	450	
			Rock to Site	70		
Warm Mix Asphalt	Initial	Wearing Course 1	Virgin Aggregate	95	50	
			Bitumen	5		
		Wearing Course 2	Virgin Aggregate	95	100	
			Bitumen	5		
		Subbase 1 (Granular A)	RAP to site	30	150	
			Gravel to site	70		
		Subbase 2 (Granular B)	RAP to site	30	450	
			Rock to Site	70		
Pervious Concrete	Initial	Wearing Course 1	Virgin Aggregate	63	150	
			Cement	16		
			Water	13		
		Subbase 1 (Drainage layer)	Rock to Site	100	600	

Table C.2 – Initial Construction PaLATE Input (Laneway)

Process	Initial or Maint.	Layer	Material	Percent	Layer Depth	Width (m)
HMA	Initial	Wearing Course 1 (Superpave 12.5)	Virgin Aggregate	95	40	5.5
			Bitumen	5		
		Wearing Course 2 (Super Pave 19.0)	Virgin Aggregate	95	75	
			Bitumen	5		
		Subbase 1 (Granular A)	RAP to Site	30	150	
			Gravel to site	70		
		Subbase 2 (Granular B)	RAP to site	30	300	
			Rock to Site	70		
Porous Asphalt	Initial	Wearing Course 1	Virgin Aggregate	93	115	
			Bitumen	7		
		Subbase 1 (Drainage layer)	Rock to Site	100	450	
Asphalt with 20%/15% RAP	Initial	Wearing Course 1 (Superpave 12.5)	Virgin Aggregate	80.75	40	
			RAP	14.25		
			Bitumen	5		
		Wearing Course 2 (Superpave 19.0)	Virgin Aggregate	76	75	
			RAP	19		
			Bitumen	5		
		Subbase 1 (Granular A)	RAP to site	30	150	
			Gravel to site	70		
		Subbase 2 (Granular B)	RAP to site	30	300	
			Rock to Site	70		
Asphalt with 3% RAS	Initial	Wearing Course 1 (Superpave 12.5)	Virgin Aggregate	95	40	
			Bitumen	4		
			RAS	1		
		Wearing Course 2 (Superpave 19.0)	Virgin Aggregate	95	75	
			Bitumen	4		
			RAS	1		
		Subbase 1 (Granular A)	RAP to site	30	150	
			Gravel to site	70		
		Subbase 2 (Granular B)	RAP to site	30	300	
			Rock to Site	70		
Warm Mix Asphalt	Initial	Wearing Course 1	Virgin Aggregate	95	40	
			Bitumen	5		
		Wearing Course 2	Virgin Aggregate	95	75	
			Bitumen	5		
		Subbase 1 (Granular A)	RAP to site	30	150	
			Gravel to site	70		
		Subbase 2 (Granular B)	RAP to site	30	300	
			Rock to Site	70		
Pervious Concrete	Initial	Wearing Course 1	Virgin Aggregate	63	115	
			Cement	16		
			Water	13		
		Subbase 1 (Drainage layer)	Rock to Site	100	450	

Table C.3 – Initial Construction PaLATE Input (Local)

Process	Initial or Maint.	Layer	Material	Percent	Layer Depth	Width (m)
HMA	Initial	Wearing Course 1 (Superpave 12.5)	Virgin Aggregate	95	40	8.5
			Bitumen	5		
		Wearing Course 2 (Super Pave 19.0)	Virgin Aggregate	95	75	
			Bitumen	5		
		Subbase 1 (Granular A)	RAP to Site	30	150	
			Gravel to site	70		
		Subbase 2 (Granular B)	RAP to site	30	300	
			Rock to Site	70		
Porous Asphalt	Initial	Wearing Course 1	Virgin Aggregate	93	115	
			Bitumen	7		
		Subbase 1 (Drainage layer)	Rock to Site	100	450	
Asphalt with 20%/15% RAP	Initial	Wearing Course 1 (Superpave 12.5)	Virgin Aggregate	80.75	40	
			RAP	14.25		
			Bitumen	5		
		Wearing Course 2 (Superpave 19.0)	Virgin Aggregate	76	75	
			RAP	19		
			Bitumen	5		
		Subbase 1 (Granular A)	RAP to site	30	150	
			Gravel to site	70		
		Subbase 2 (Granular B)	RAP to site	30	300	
			Rock to Site	70		
Asphalt with 3% RAS	Initial	Wearing Course 1 (Superpave 12.5)	Virgin Aggregate	95	40	
			Bitumen	4		
			RAS	1		
		Wearing Course 2 (Superpave 19.0)	Virgin Aggregate	95	75	
			Bitumen	4		
			RAS	1		
		Subbase 1 (Granular A)	RAP to site	30	150	
			Gravel to site	70		
		Subbase 2 (Granular B)	RAP to site	30	300	
			Rock to Site	70		
Warm Mix Asphalt	Initial	Wearing Course 1	Virgin Aggregate	95	40	
			Bitumen	5		
		Wearing Course 2	Virgin Aggregate	95	75	
			Bitumen	5		
		Subbase 1 (Granular A)	RAP to site	30	150	
			Gravel to site	70		
		Subbase 2 (Granular B)	RAP to site	30	300	
			Rock to Site	70		
Pervious Concrete	Initial	Wearing Course 1	Virgin Aggregate	63	115	
			Cement	16		
			Water	13		
		Subbase 1 (Drainage layer)	Rock to Site	100	450	

Table C.4 – Initial Construction PaLATE Input (Major Collector)

Process	Initial or Maint.	Layer	Material	Percent	Layer Depth	Width (m)
HMA	Initial	Wearing Course 1 (Superpave 12.5)	Virgin Aggregate	95	50	13.0
			Bitumen	5		
		Wearing Course 2 (Super Pave 19.0)	Virgin Aggregate	95	100	
			Bitumen	5		
		Subbase 1 (Granular A)	RAP to Site	30	150	
			Gravel to site	70		
		Subbase 2 (Granular B)	RAP to site	30	450	
			Rock to Site	70		
Porous Asphalt	Initial	Wearing Course 1	Virgin Aggregate	93	150	
			Bitumen	7		
		Subbase 1 (Drainage layer)	Rock to Site	100	600	
Asphalt with 20%/15% RAP	Initial	Wearing Course 1 (Superpave 12.5)	Virgin Aggregate	80.75	50	
			RAP	14.25		
			Bitumen	5		
		Wearing Course 2 (Superpave 19.0)	Virgin Aggregate	76	100	
			RAP	19		
			Bitumen	5		
		Subbase 1 (Granular A)	RAP to site	30	150	
			Gravel to site	70		
		Subbase 2 (Granular B)	RAP to site	30	450	
			Rock to Site	70		
Asphalt with 3% RAS	Initial	Wearing Course 1 (Superpave 12.5)	Virgin Aggregate	95	50	
			Bitumen	4		
			RAS	1		
		Wearing Course 2 (Superpave 19.0)	Virgin Aggregate	95	100	
			Bitumen	4		
			RAS	1		
		Subbase 1 (Granular A)	RAP to site	30	150	
			Gravel to site	70		
		Subbase 2 (Granular B)	RAP to site	30	450	
			Rock to Site	70		
Warm Mix Asphalt	Initial	Wearing Course 1	Virgin Aggregate	95	50	
			Bitumen	5		
		Wearing Course 2	Virgin Aggregate	95	100	
			Bitumen	5		
		Subbase 1 (Granular A)	RAP to site	30	150	
			Gravel to site	70		
		Subbase 2 (Granular B)	RAP to site	30	450	
			Rock to Site	70		
Pervious Concrete	Initial	Wearing Course 1	Virgin Aggregate	63	150	
			Cement	16		
			Water	13		
		Subbase 1 (Drainage layer)	Rock to Site	100	600	

Table C.5 – Initial Construction PaLATE Input (Minor Collector)

Process	Initial or Maint.	Layer	Material	Percent	Layer Depth	Width (m)
HMA	Initial	Wearing Course 1 (Superpave 12.5)	Virgin Aggregate	95	50	11.0
			Bitumen	5		
		Wearing Course 2 (Super Pave 19.0)	Virgin Aggregate	95	100	
			Bitumen	5		
		Subbase 1 (Granular A)	RAP to Site	30	150	
			Gravel to site	70		
		Subbase 2 (Granular B)	RAP to site	30	450	
			Rock to Site	70		
Porous Asphalt	Initial	Wearing Course 1	Virgin Aggregate	93	150	
			Bitumen	7		
		Subbase 1 (Drainage layer)	Rock to Site	100	600	
Asphalt with 20%/15% RAP	Initial	Wearing Course 1 (Superpave 12.5)	Virgin Aggregate	80.75	50	
			RAP	14.25		
			Bitumen	5		
		Wearing Course 2 (Superpave 19.0)	Virgin Aggregate	76	100	
			RAP	19		
			Bitumen	5		
		Subbase 1 (Granular A)	RAP to site	30	150	
			Gravel to site	70		
		Subbase 2 (Granular B)	RAP to site	30	450	
			Rock to Site	70		
Asphalt with 3% RAS	Initial	Wearing Course 1 (Superpave 12.5)	Virgin Aggregate	95	50	
			Bitumen	4		
			RAS	1		
		Wearing Course 2 (Superpave 19.0)	Virgin Aggregate	95	100	
			Bitumen	4		
			RAS	1		
		Subbase 1 (Granular A)	RAP to site	30	150	
			Gravel to site	70		
		Subbase 2 (Granular B)	RAP to site	30	450	
			Rock to Site	70		
Warm Mix Asphalt	Initial	Wearing Course 1	Virgin Aggregate	95	50	
			Bitumen	5		
		Wearing Course 2	Virgin Aggregate	95	100	
			Bitumen	5		
		Subbase 1 (Granular A)	RAP to site	30	150	
			Gravel to site	70		
		Subbase 2 (Granular B)	RAP to site	30	450	
			Rock to Site	70		
Pervious Concrete	Initial	Wearing Course 1	Virgin Aggregate	63	150	
			Cement	16		
			Water	13		
		Subbase 1 (Drainage layer)	Rock to Site	100	600	

INPUT – Rehabilitation

Table C.6 – Rehabilitation PaLATE Input (Industrial)

Process	Initial or Maint.	Layer	Material	Percent	Layer Depth (mm)	Width (m)
Cold In-Place	Maint.	Wearing Course 1 (New Layer)	Virgin Aggregate	95	50	13.0
			Bitumen	5		
		Wearing Course 2 (Existing Layer)	RAP Volume	100	100	
			Asphalt Emulsion	2		
Cold In-Place with Expanded Asphalt Mix	Maint.	Wearing Course 1 (New Layer)	Virgin Aggregate	95	50	
			Bitumen	5		
		Wearing Course 2 (Existing Layer)	RAP Volume	100	100	
			Bitumen	2		
Full Depth Reclamation	Maint.	Wearing Course 1 (New layer)	Virgin Aggregate	95	50	
			Bitumen	5		
		Wearing Course 2	Existing Layer Volume	100	150	
Mill and HMA Overlay	Maint.	Wearing Course 1 (Superpave 12.5)	Virgin Aggregate	95	50	
			Bitumen	5		
		Wearing Course 2 (Superpave 19.0)	Virgin Aggregate	95	100	
			Bitumen	5		
		Wearing Course 3 (Disposed)	RAP Disposal	100	100	
Mill and HMA Overlay with 15% RAP	Maint.	Wearing Course 1 (Superpave 12.5 with 15% RAP)	Virgin Aggregate	80.75	50	
			RAP	14.25		
			Bitumen	5		
		Wearing Course 2 (Superpave 19.0 with 20% RAP)	Virgin Aggregate	76	100	
			RAP	19		
			Bitumen	5		
		Wearing Course 3 (Disposed)	RAP Disposal	100	100	
Microsurfacing	Maint.	Wearing Course 1	Microsurfacing mix	100	10	

Table C.7 – Rehabilitation PaLATE Input (Laneway)

Process	Initial or Maint.	Layer	Material	Percent	Layer Depth (mm)	Width (m)
Cold In-Place	Maint.	Wearing Course 1 (New Layer)	Virgin Aggregate	95	40	5.5
			Bitumen	5		
		Wearing Course 2 (Existing Layer)	RAP Volume	100	100	
			Asphalt Emulsion	2		
Cold In-Place with Expanded Asphalt Mix	Maint.	Wearing Course 1 (New Layer)	Virgin Aggregate	95	40	
			Bitumen	5		
		Wearing Course 2 (Existing Layer)	RAP Volume	100	100	
			Bitumen	2		
Full Depth Reclamation	Maint.	Wearing Course 1 (New layer)	Virgin Aggregate	95	40	
			Bitumen	5		
		Wearing Course 2 (Pulverized Layer)	Existing Layer Volume	76.7	150	
			Base Layer Volume	23.3		
Mill and HMA Overlay	Maint.	Wearing Course 1 (Superpave 12.5)	Virgin Aggregate	95	40	
			Bitumen	5		
		Wearing Course 2 (Superpave 19.0)	Virgin Aggregate	95	75	
			Bitumen	5		
		Wearing Course 3 (Disposed)	RAP Disposal	100	100	
Mill and HMA Overlay with 15% RAP	Maint.	Wearing Course 1 (Superpave 12.5 with 15% RAP)	Virgin Aggregate	80.75	40	
			RAP	14.25		
			Bitumen	5		
		Wearing Course 2 (Superpave 19.0 with 20% RAP)	Virgin Aggregate	76	75	
			RAP	19		
			Bitumen	5		
		Wearing Course 3 (Disposed)	RAP Disposal	100	100	
Microsurfacing	Maint.	Wearing Course 1	Microsurfacing mix	100	10	

Table C.8 – Rehabilitation PaLATE Input (Local)

Process	Initial or Maint.	Layer	Material	Percent	Layer Depth (mm)	Width (m)
Cold In-Place	Maint.	Wearing Course 1 (New Layer)	Virgin Aggregate	95	40	8.5
			Bitumen	5		
		Wearing Course 2 (Existing Layer)	RAP Volume	100	100	
			Asphalt Emulsion	2		
Cold In-Place with Expanded Asphalt Mix	Maint.	Wearing Course 1 (New Layer)	Virgin Aggregate	95	40	
			Bitumen	5		
		Wearing Course 2 (Existing Layer)	RAP Volume	100	100	
			Bitumen	2		
Full Depth Reclamation	Maint.	Wearing Course 1 (New layer)	Virgin Aggregate	95	40	
			Bitumen	5		
		Wearing Course 2 (Pulverized Layer)	Existing Layer Volume	76.7	150	
			Base Layer Volume	23.3		
Mill and HMA Overlay	Maint.	Wearing Course 1 (Superpave 12.5)	Virgin Aggregate	95	40	
			Bitumen	5		
		Wearing Course 2 (Superpave 19.0)	Virgin Aggregate	95	75	
			Bitumen	5		
		Wearing Course 3 (Disposed)	RAP Disposal	100	100	
Mill and HMA Overlay with 15% RAP	Maint.	Wearing Course 1 (Superpave 12.5 with 15% RAP)	Virgin Aggregate	80.75	40	
			RAP	14.25		
			Bitumen	5		
		Wearing Course 2 (Superpave 19.0 with 20% RAP)	Virgin Aggregate	76	75	
			RAP	19		
			Bitumen	5		
		Wearing Course 3 (Disposed)	RAP Disposal	100	100	
Microsurfacing	Maint.	Wearing Course 1	Microsurfacing mix	100	10	

Table C.9 – Rehabilitation PaLATE Input (Major Collector)

Process	Initial or Maint.	Layer	Material	Percent	Layer Depth (mm)	Width (m)
Cold In-Place	Maint.	Wearing Course 1 (New Layer)	Virgin Aggregate	95	50	13.0
			Bitumen	5		
		Wearing Course 2 (Existing Layer)	RAP Volume	100	100	
			Asphalt Emulsion	2		
Cold In-Place with Expanded Asphalt Mix	Maint.	Wearing Course 1 (New Layer)	Virgin Aggregate	95	50	
			Bitumen	5		
		Wearing Course 2 (Existing Layer)	RAP Volume	100	100	
			Bitumen	2		
Full Depth Reclamation	Maint.	Wearing Course 1 (New layer)	Virgin Aggregate	95	50	
			Bitumen	5		
		Wearing Course 2	Existing Layer Volume	100	150	
Mill and HMA Overlay	Maint.	Wearing Course 1 (Superpave 12.5)	Virgin Aggregate	95	50	
			Bitumen	5		
		Wearing Course 2 (Superpave 19.0)	Virgin Aggregate	95	100	
			Bitumen	5		
		Wearing Course 3 (Disposed)	RAP Disposal	100	100	
Mill and HMA Overlay with 15% RAP	Maint.	Wearing Course 1 (Superpave 12.5 with 15% RAP)	Virgin Aggregate	80.75	50	
			RAP	14.25		
			Bitumen	5		
		Wearing Course 2 (Superpave 19.0 with 20% RAP)	Virgin Aggregate	76	100	
			RAP	19		
			Bitumen	5		
		Wearing Course 3 (Disposed)	RAP Disposal	100	100	
Microsurfacing	Maint.	Wearing Course 1	Microsurfacing mix	100	10	

Table C.10 – Rehabilitation PaLATE Input (Minor Collector)

Process	Initial or Maint.	Layer	Material	Percent	Layer Depth (mm)	Width (m)
Cold In-Place	Maint.	Wearing Course 1 (New Layer)	Virgin Aggregate	95	50	11.0
			Bitumen	5		
		Wearing Course 2 (Existing Layer)	RAP Volume	100	100	
			Asphalt Emulsion	2		
Cold In-Place with Expanded Asphalt Mix	Maint.	Wearing Course 1 (New Layer)	Virgin Aggregate	95	50	
			Bitumen	5		
		Wearing Course 2 (Existing Layer)	RAP Volume	100	100	
			Bitumen	2		
Full Depth Reclamation	Maint.	Wearing Course 1 (New layer)	Virgin Aggregate	95	50	
			Bitumen	5		
		Wearing Course 2	Existing Layer Volume	100	150	
Mill and HMA Overlay	Maint.	Wearing Course 1 (Superpave 12.5)	Virgin Aggregate	95	50	
			Bitumen	5		
		Wearing Course 2 (Superpave 19.0)	Virgin Aggregate	95	100	
			Bitumen	5		
		Wearing Course 3 (Disposed)	RAP Disposal	100	100	
Mill and HMA Overlay with 15% RAP	Maint.	Wearing Course 1 (Superpave 12.5 with 15% RAP)	Virgin Aggregate	80.75	50	
			RAP	14.25		
			Bitumen	5		
		Wearing Course 2 (Superpave 19.0 with 20% RAP)	Virgin Aggregate	76	100	
			RAP	19		
			Bitumen	5		
		Wearing Course 3 (Disposed)	RAP Disposal	100	100	
Microsurfacing	Maint.	Wearing Course 1	Microsurfacing mix	100	10	

Appendix C
PaLATE Output

Warm Mix Asphalt Quantification

The PaLATE software is not designed to quantify the economical or environmental impact associated with the utilization of warm mix asphalt (WMA). For the purposes of this report a short literature review evaluating current WMA technologies is performed to determine the environmental savings of WMA. This section of the report summarizes the results of the conducted literature review.

Table D.**1** displays the results of the conducted literature review. Environmental savings were observed in following criteria: energy consumption, CO_2, CO, NO_x and SO_2. It should be noted that these results provide an approximation for the environmental savings associated with WMA; differing WMA technologies have different environmental impacts. The percentages under the result column represent the suggested reductions associated with each criterion. These reductions were estimated by taking the average of the three corresponding WMA technology reductions. The only exception to this was carbon monoxide; Evotherm reports a 63% reduction while the other two technologies report 8% and 10%. Therefore, the lower percentages were favoured.

Table D.1 – Warm Mix Asphalt Literature Review Results

Criteria	1. WAMfoam	2. Double Barrel Green Process	3. Evotherm	Result
Energy	35%	24%	30%-60%	34%
CO_2	35%	10%	46%	30%
CO	8%	10%	63%	15%
NO_x	60%	10%	58%	43%
SO_2	25%	N/A	41%	33%

1 - [Hassan, 2009] Hassan, M. (2009). Life Cycle Assessment of Warm Mix Asphalt and Economic and Environmental Perspective. Lousiana: Louisiana State University.
2 - [MWV, 2012] MWV Specialty Chemicals. (2012). Evotherm Warm Mix Asphalt. Retrieved February 16, 2012, from MWV Specialty Chemicals: http://www.meadwestvaco.com/mwv/groups/content/documents/document/mwv006575.pdf
3 - [Wakefield, 2011] Wakefield, A. (2011). A Comprehensive Evaluation of Hot Mix Asphalt versus Chemically Modified Warm Mix Asphalt. Waterloo: University of Waterloo.

OUTPUT - Tabular

Table D.2 – PaLATE Results (Industrial)

Process	Energy [MJ]	Water Consumption [kg]	CO_2 [Mg] = GWP	NO_x [kg]	PM_{10} [kg]	SO_2 [kg]	CO [kg]	Hg [g]	Pb [g]
Total Emissions									
HMA (Control)	6358572	1384	379	3984	3441	53638	1002	4	255
HMA with RAP	6194255	1360	369	3897	3272	53624	985	4	252
HMA with RAS	5927905	1207	355	3843	3419	52990	901	3	220
Porous Asphalt	8440647	1919	515	4974	4728	53991	1352	6	353
Pervious Concrete	8966802	2661	633	7531	5384	3662	2791	7	539
Warm Mix Asphalt	4196657	1384	266	2271	3441	35938	852	4	255
Annual Emissions									
HMA (Control)	423904.8	92.3	25.3	265.6	229.4	3575.9	66.8	0.3	17.0
HMA with RAP	412950.3	90.7	24.6	259.8	218.1	3574.9	65.7	0.3	16.8
HMA with RAS	395193.7	80.5	23.7	256.2	227.9	3532.7	60.1	0.2	14.7
Porous Asphalt	562709.8	128.0	34.4	331.6	315.2	3599.4	90.1	0.4	23.5
Pervious Concrete	448340.1	133.1	31.6	376.5	269.2	183.1	139.6	0.4	26.9
Warm Mix Asphalt	279777.1	92.3	17.7	151.4	229.4	2395.8	56.8	0.3	17.0
Percent Compared to Control									
HMA (Control)	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
HMA with RAP	2.58%	1.78%	2.63%	2.18%	4.93%	0.03%	1.76%	0.21%	1.38%
HMA with RAS	6.77%	12.83%	6.36%	3.52%	0.66%	1.21%	10.13%	17.83%	13.75%
Porous Asphalt	-32.74%	-38.64%	-35.87%	-24.87%	-37.38%	-0.66%	-34.88%	-38.27%	-38.25%
Pervious Concrete	-5.76%	-44.15%	-25.08%	-41.79%	-17.34%	94.88%	-108.85%	-31.59%	-58.35%
Warm Mix Asphalt	34.00%	0.00%	30.00%	43.00%	0.00%	33.00%	15.00%	0.00%	0.00%

Process	Energy [MJ]	Water Consumption [kg]	CO_2 [Mg] = GWP	NO_x [kg]	PM_{10} [kg]	SO_2 [kg]	CO [kg]	Hg [g]	Pb [g]
Total Emissions									
Mill and HMA Overlay (Control)	3821647	1030	198	1955	1073	53392	639	3.87	197
Mill and HMA Overlay with RAP	3657330	1005	188	1868	903	53377	622	3.86	194
Cold In-Place Recycling	1797067	556	96	859	388	18642	340	2.16	106
CIREAM	1873852	588	100	883	392	18664	358	2.30	112
Full Depth Reclamation	1281481	343	66	666	360	17798	216	1.29	66
Microsurfacing	209670	53	11	127	74	3475	53	0.31	16
Annual Emissions									
Mill and HMA Overlay (Control)	347422.4	93.7	18.0	177.7	97.5	4853.8	58.1	0.35	17.9
Mill and HMA Overlay with RAP	332484.6	91.4	17.1	169.8	82.1	4852.5	56.5	0.35	17.6
Cold In-Place Recycling	163369.8	50.5	8.7	78.1	35.3	1694.8	30.9	0.20	9.6
CIREAM	170350.2	53.4	9.1	80.3	35.7	1696.8	32.6	0.21	10.2
Full Depth Reclamation	85432.1	22.9	4.4	44.4	24.0	1186.6	14.4	0.09	4.4
Microsurfacing	26208.7	6.7	1.4	15.8	9.2	434.4	6.6	0.04	2.0
Percent Compared to Control									
Mill and HMA Overlay (Control)	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Mill and HMA Overlay with RAP	4.30%	2.40%	5.04%	4.44%	15.83%	0.03%	2.76%	0.23%	1.78%
Cold In-Place Recycling	52.98%	46.07%	51.62%	56.06%	63.81%	65.08%	46.86%	44.25%	46.17%
CIREAM	50.97%	42.94%	49.41%	54.82%	63.43%	65.04%	43.98%	40.72%	42.95%
Full Depth Reclamation	75.41%	75.56%	75.34%	75.01%	75.40%	75.55%	75.20%	75.56%	75.56%
Microsurfacing	92.46%	92.87%	92.27%	91.09%	90.56%	91.05%	88.59%	89.13%	88.80%

Table D.3 – PaLATE Results (Laneway)

Process	Energy [MJ]	Water Consumption [kg]	CO_2 [Mg] = GWP	NO_x [kg]	PM_{10} [kg]	SO_2 [kg]	CO [kg]	Hg [g]	Pb [g]
Total Emissions									
HMA (Control)	2024450	443	120	1270	1078	17353	321	1	82
HMA with RAP	1971485	435	117	1242	1023	17348	316	1	81
HMA with RAS	1885098	385	113	1224	1070	17143	288	1	70
Porous Asphalt	2711038	619	165	1594	1508	17506	435	2	114
Pervious Concrete	2880983	859	203	2423	1720	1185	902	2	174
Warm Mix Asphalt	1336137	443	84	724	1078	11626	273	1	82
Annual Emissions									
HMA (Control)	134963.3	29.5	8.0	84.7	71.9	1156.9	21.4	0.1	5.4
HMA with RAP	131432.3	29.0	7.8	82.8	68.2	1156.5	21.0	0.1	5.4
HMA with RAS	125673.2	25.7	7.5	81.6	71.4	1142.9	19.2	0.1	4.7
Porous Asphalt	180735.8	41.2	11.0	106.3	100.5	1167.1	29.0	0.1	7.6
Pervious Concrete	144049.2	43.0	10.2	121.1	86.0	59.3	45.1	0.1	8.7
Warm Mix Asphalt	89075.8	29.5	5.6	48.3	71.9	775.1	18.2	0.1	5.4
Percent Compared to Control									
HMA (Control)	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
HMA with RAP	2.62%	1.80%	2.67%	2.21%	5.07%	0.03%	1.77%	0.21%	1.39%
HMA with RAS	6.88%	12.99%	6.48%	3.57%	0.68%	1.21%	10.23%	17.89%	13.89%
Porous Asphalt	-33.91%	-39.83%	-37.27%	-25.53%	-39.93%	-0.88%	-35.41%	-38.80%	-39.25%
Pervious Concrete	-6.73%	-45.61%	-26.60%	-43.09%	-19.71%	94.88%	-110.52%	-32.13%	-59.77%
Warm Mix Asphalt	34.00%	0.00%	30.00%	43.00%	0.00%	33.00%	15.00%	0.00%	0.00%

Process	Energy [MJ]	Water Consumption [kg]	CO_2 [Mg] = GWP	NO_x [kg]	PM_{10} [kg]	SO_2 [kg]	CO [kg]	Hg [g]	Pb [g]
Total Emissions									
Mill and HMA Overlay (Control)	1236576	333	64	633	347	17276	207	1.25	64
Mill and HMA Overlay with RAP	1183611	325	61	605	292	17271	201	1.25	63
Cold In-Place Recycling	650866	206	35	307	133	6358	125	0.80	39
CIREAM	683352	219	37	318	135	6368	133	0.86	42
Full Depth Reclamation	432734	116	22	226	121	6001	73	0.44	22
Microsurfacing	88707	23	5	54	31	1470	22	0.13	7
Annual Emissions									
Mill and HMA Overlay (Control)	112416.0	30.3	5.8	57.5	31.6	1570.6	18.8	0.11	5.8
Mill and HMA Overlay with RAP	107601.0	29.6	5.5	55.0	26.6	1570.1	18.3	0.11	5.7
Cold In-Place Recycling	59169.7	18.7	3.2	28.0	12.1	578.0	11.4	0.07	3.6
CIREAM	62122.9	19.9	3.3	28.9	12.3	578.9	12.1	0.08	3.8
Full Depth Reclamation	28848.9	7.7	1.5	15.1	8.1	400.1	4.9	0.03	1.5
Microsurfacing	11088.3	2.8	0.6	6.7	3.9	183.8	2.8	0.02	0.8
Percent Compared to Control									
Mill and HMA Overlay (Control)	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Mill and HMA Overlay with RAP	4.28%	2.39%	5.02%	4.43%	15.77%	0.03%	2.75%	0.23%	1.78%
Cold In-Place Recycling	47.37%	38.34%	45.59%	51.39%	61.56%	63.20%	39.36%	35.95%	38.47%
CIREAM	44.74%	34.25%	42.71%	49.77%	61.06%	63.14%	35.60%	31.33%	34.25%
Full Depth Reclamation	74.34%	74.53%	74.25%	73.82%	74.35%	74.53%	74.06%	74.53%	74.53%
Microsurfacing	90.14%	90.68%	89.90%	88.34%	87.65%	88.30%	85.08%	85.79%	85.36%

Table D.4 – PaLATE Results (Local)

Process	Energy [MJ]	Water Consumption [kg]	CO_2 [Mg] = GWP	NO_x [kg]	PM_{10} [kg]	SO_2 [kg]	CO [kg]	Hg [g]	Pb [g]
Total Emissions									
HMA (Control)	3128695	684	186	1962	1666	26818	496	2	126
HMA with RAP	3046840	672	181	1919	1581	26811	488	2	125
HMA with RAS	2913334	595	174	1892	1654	26494	446	2	109
Porous Asphalt	4189786	956	255	2463	2331	27055	672	3	176
Pervious Concrete	4452429	1328	314	3744	2659	1831	1393	4	269
Warm Mix Asphalt	2064939	684	130	1119	1666	17968	422	2	126
Annual Emissions									
HMA (Control)	208579.7	45.6	12.4	130.8	111.0	1787.9	33.1	0.1	8.4
HMA with RAP	203122.7	44.8	12.1	127.9	105.4	1787.4	32.5	0.1	8.3
HMA with RAS	194222.2	39.7	11.6	126.2	110.3	1766.3	29.7	0.1	7.2
Porous Asphalt	279319.0	63.7	17.0	164.2	155.4	1803.7	44.8	0.2	11.7
Pervious Concrete	222621.4	66.4	15.7	187.2	132.9	91.6	69.7	0.2	13.4
Warm Mix Asphalt	137662.6	45.6	8.7	74.6	111.0	1197.9	28.1	0.1	8.4
Percent Compared to Control									
HMA (Control)	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
HMA with RAP	2.62%	1.80%	2.67%	2.21%	5.07%	0.03%	1.77%	0.21%	1.39%
HMA with RAS	6.88%	12.99%	6.48%	3.57%	0.68%	1.21%	10.23%	17.89%	13.89%
Porous Asphalt	-33.91%	-39.83%	-37.27%	-25.53%	-39.93%	-0.88%	-35.41%	-38.80%	-39.25%
Pervious Concrete	-6.73%	-45.61%	-26.60%	-43.09%	-19.71%	94.88%	-110.52%	-32.13%	-59.77%
Warm Mix Asphalt	34.00%	0.00%	30.00%	43.00%	0.00%	33.00%	15.00%	0.00%	0.00%

Process	Energy [MJ]	Water Consumption [kg]	CO_2 [Mg] = GWP	NO_x [kg]	PM_{10} [kg]	SO_2 [kg]	CO [kg]	Hg [g]	Pb [g]
Total Emissions									
Mill and HMA Overlay (Control)	1911072	515	99	978	536	26699	320	1.94	99
Mill and HMA Overlay with RAP	1829217	503	94	934	452	26692	311	1.93	97
Cold In-Place Recycling	1005884	318	54	475	206	9826	194	1.24	61
CIREAM	1056090	339	57	491	209	9841	206	1.33	65
Full Depth Reclamation	668770	179	35	349	188	9275	113	0.67	34
Microsurfacing	137092	35	7	83	48	2272	35	0.20	10
Annual Emissions									
Mill and HMA Overlay (Control)	173733.8	46.8	9.0	88.9	48.8	2427.2	29.1	0.18	9.0
Mill and HMA Overlay with RAP	166292.5	45.7	8.5	84.9	41.1	2426.6	28.3	0.18	8.8
Cold In-Place Recycling	91444.0	28.9	4.9	43.2	18.7	893.3	17.6	0.11	5.5
CIREAM	96008.1	30.8	5.1	44.6	19.0	894.6	18.7	0.12	5.9
Full Depth Reclamation	44584.7	11.9	2.3	23.3	12.5	618.3	7.5	0.04	2.3
Microsurfacing	17136.5	4.4	0.9	10.4	6.0	284.0	4.3	0.03	1.3
Percent Compared to Control									
Mill and HMA Overlay (Control)	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Mill and HMA Overlay with RAP	4.28%	2.39%	5.02%	4.43%	15.77%	0.03%	2.75%	0.23%	1.78%
Cold In-Place Recycling	47.37%	38.34%	45.59%	51.39%	61.56%	63.20%	39.36%	35.95%	38.47%
CIREAM	44.74%	34.25%	42.71%	49.77%	61.06%	63.14%	35.60%	31.33%	34.25%
Full Depth Reclamation	74.34%	74.53%	74.25%	73.82%	74.35%	74.53%	74.06%	74.53%	74.53%
Microsurfacing	90.14%	90.68%	89.90%	88.34%	87.65%	88.30%	85.08%	85.79%	85.36%

Table D.5 – PaLATE Results (Major Collector)

Process	Energy [MJ]	Water Consumption [kg]	CO_2 [Mg] = GWP	NO_x [kg]	PM_{10} [kg]	SO_2 [kg]	CO [kg]	Hg [g]	Pb [g]
Total Emissions									
HMA (Control)	6358572	1384	379	3984	3441	53638	1002	4	255
HMA with RAP	6194255	1360	369	3897	3272	53624	985	4	252
HMA with RAS	5927905	1207	355	3843	3419	52990	901	3	220
Porous Asphalt	8440647	1919	515	4974	4728	53991	1352	6	353
Pervious Concrete	8966802	2661	633	7531	5384	3662	2791	7	539
Warm Mix Asphalt	4196657	1384	266	2271	3441	35938	852	4	255
Annual Emissions									
HMA (Control)	423904.8	92.3	25.3	265.6	229.4	3575.9	66.8	0.3	17.0
HMA with RAP	412950.3	90.7	24.6	259.8	218.1	3574.9	65.7	0.3	16.8
HMA with RAS	395193.7	80.5	23.7	256.2	227.9	3532.7	60.1	0.2	14.7
Porous Asphalt	562709.8	128.0	34.4	331.6	315.2	3599.4	90.1	0.4	23.5
Pervious Concrete	448340.1	133.1	31.6	376.5	269.2	183.1	139.6	0.4	26.9
Warm Mix Asphalt	279777.1	92.3	17.7	151.4	229.4	2395.8	56.8	0.3	17.0
Percent Compared to Control									
HMA (Control)	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
HMA with RAP	2.58%	1.78%	2.63%	2.18%	4.93%	0.03%	1.76%	0.21%	1.38%
HMA with RAS	6.77%	12.83%	6.36%	3.52%	0.66%	1.21%	10.13%	17.83%	13.75%
Porous Asphalt	-32.74%	-38.64%	-35.87%	-24.87%	-37.38%	-0.66%	-34.88%	-38.27%	-38.25%
Pervious Concrete	-5.76%	-44.15%	-25.08%	-41.79%	-17.34%	94.88%	-108.85%	-31.59%	-58.35%
Warm Mix Asphalt	34.00%	0.00%	30.00%	43.00%	0.00%	33.00%	15.00%	0.00%	0.00%

Process	Energy [MJ]	Water Consumption [kg]	CO_2 [Mg] = GWP	NO_x [kg]	PM_{10} [kg]	SO_2 [kg]	CO [kg]	Hg [g]	Pb [g]
Total Emissions									
Mill and HMA Overlay (Control)	3821647	1030	198	1955	1073	53392	639	3.87	197
Mill and HMA Overlay with RAP	3657330	1005	188	1868	903	53377	622	3.86	194
Cold In-Place Recycling	1797067	556	96	859	388	18642	340	2.16	106
CIREAM	1873852	588	100	883	392	18664	358	2.30	112
Full Depth Reclamation	1281481	343	66	666	360	17798	216	1.29	66
Microsurfacing	209670	53	11	127	74	3475	53	0.31	16
Annual Emissions									
Mill and HMA Overlay (Control)	347422.4	93.7	18.0	177.7	97.5	4853.8	58.1	0.35	17.9
Mill and HMA Overlay with RAP	332484.6	91.4	17.1	169.8	82.1	4852.5	56.5	0.35	17.6
Cold In-Place Recycling	163369.8	50.5	8.7	78.1	35.3	1694.8	30.9	0.20	9.6
CIREAM	170350.2	53.4	9.1	80.3	35.7	1696.8	32.6	0.21	10.2
Full Depth Reclamation	85432.1	22.9	4.4	44.4	24.0	1186.6	14.4	0.09	4.4
Microsurfacing	26208.7	6.7	1.4	15.8	9.2	434.4	6.6	0.04	2.0
Percent Compared to Control									
Mill and HMA Overlay (Control)	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Mill and HMA Overlay with RAP	4.30%	2.40%	5.04%	4.44%	15.83%	0.03%	2.76%	0.23%	1.78%
Cold In-Place Recycling	52.98%	46.07%	51.62%	56.06%	63.81%	65.08%	46.86%	44.25%	46.17%
CIREAM	50.97%	42.94%	49.41%	54.82%	63.43%	65.04%	43.98%	40.72%	42.95%
Full Depth Reclamation	75.41%	75.56%	75.34%	75.01%	75.40%	75.55%	75.20%	75.56%	75.56%
Microsurfacing	92.46%	92.87%	92.27%	91.09%	90.56%	91.05%	88.59%	89.13%	88.80%

Table D.6 – PaLATE Results (Minor Collector)

Process	Energy [MJ]	Water Consumption [kg]	CO_2 [Mg] = GWP	NO_x [kg]	PM_{10} [kg]	SO_2 [kg]	CO [kg]	Hg [g]	Pb [g]
Total Emissions									
HMA (Control)	5380330	1171	321	3371	2912	45386	848	4	216
HMA with RAP	5241293	1151	313	3297	2768	45374	833	4	213
HMA with RAS	5015920	1021	301	3252	2893	44838	762	3	186
Porous Asphalt	7142086	1624	436	4209	4000	45685	1144	5	298
Pervious Concrete	7587294	2252	535	6372	4556	3099	2362	6	456
Warm Mix Asphalt	3551018	1171	225	1921	2912	30409	721	4	216
Annual Emissions									
HMA (Control)	358688.7	78.1	21.4	224.7	194.1	3025.7	56.5	0.2	14.4
HMA with RAP	349419.5	76.7	20.8	219.8	184.6	3024.9	55.6	0.2	14.2
HMA with RAS	334394.6	68.1	20.0	216.8	192.8	2989.2	50.8	0.2	12.4
Porous Asphalt	476139.0	108.3	29.1	280.6	266.7	3045.6	76.3	0.3	19.9
Pervious Concrete	379364.7	112.6	26.8	318.6	227.8	154.9	118.1	0.3	22.8
Warm Mix Asphalt	236734.5	78.1	15.0	128.1	194.1	2027.3	48.1	0.2	14.4
Percent Compared to Control									
HMA (Control)	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
HMA with RAP	2.58%	1.78%	2.63%	2.18%	4.93%	0.03%	1.76%	0.21%	1.38%
HMA with RAS	6.77%	12.83%	6.36%	3.52%	0.66%	1.21%	10.13%	17.83%	13.75%
Porous Asphalt	-32.74%	-38.64%	-35.87%	-24.87%	-37.38%	-0.66%	-34.88%	-38.27%	-38.25%
Pervious Concrete	-5.76%	-44.15%	-25.08%	-41.79%	-17.34%	94.88%	-108.85%	-31.59%	-58.35%
Warm Mix Asphalt	34.00%	0.00%	30.00%	43.00%	0.00%	33.00%	15.00%	0.00%	0.00%

Process	Energy [MJ]	Water Consumption [kg]	CO_2 [Mg] = GWP	NO_x [kg]	PM_{10} [kg]	SO_2 [kg]	CO [kg]	Hg [g]	Pb [g]
Total Emissions									
Mill and HMA Overlay (Control)	3233701	872	167	1654	908	45178	541	3.28	167
Mill and HMA Overlay with RAP	3094664	851	159	1581	764	45166	526	3.27	164
Cold In-Place Recycling	1520596	470	81	727	328	15774	287	1.83	90
CIREAM	1585567	497	85	747	332	15793	303	1.94	95
Full Depth Reclamation	1084330	291	56	564	304	15060	183	1.09	56
Microsurfacing	177413	45	9	107	62	2940	45	0.26	14
Annual Emissions									
Mill and HMA Overlay (Control)	293972.8	79.2	15.2	150.4	82.5	4107.1	49.2	0.30	15.2
Mill and HMA Overlay with RAP	281333.1	77.3	14.4	143.7	69.4	4106.0	47.8	0.30	14.9
Cold In-Place Recycling	138236.0	42.7	7.4	66.1	29.9	1434.0	26.1	0.17	8.2
CIREAM	144142.5	45.2	7.7	67.9	30.2	1435.7	27.6	0.18	8.7
Full Depth Reclamation	72288.7	19.4	3.7	37.6	20.3	1004.0	12.2	0.07	3.7
Microsurfacing	22176.6	5.6	1.2	13.4	7.8	367.6	5.6	0.03	1.7
Percent Compared to Control									
Mill and HMA Overlay (Control)	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Mill and HMA Overlay with RAP	4.30%	2.40%	5.04%	4.44%	15.83%	0.03%	2.76%	0.23%	1.78%
Cold In-Place Recycling	52.98%	46.07%	51.62%	56.06%	63.81%	65.08%	46.86%	44.25%	46.17%
CIREAM	50.97%	42.94%	49.41%	54.82%	63.43%	65.04%	43.98%	40.72%	42.95%
Full Depth Reclamation	75.41%	75.56%	75.34%	75.01%	75.40%	75.55%	75.20%	75.56%	75.56%
Microsurfacing	92.46%	92.87%	92.27%	91.09%	90.56%	91.05%	88.59%	89.13%	88.80%

OUTPUT – Graphical (Industrial)

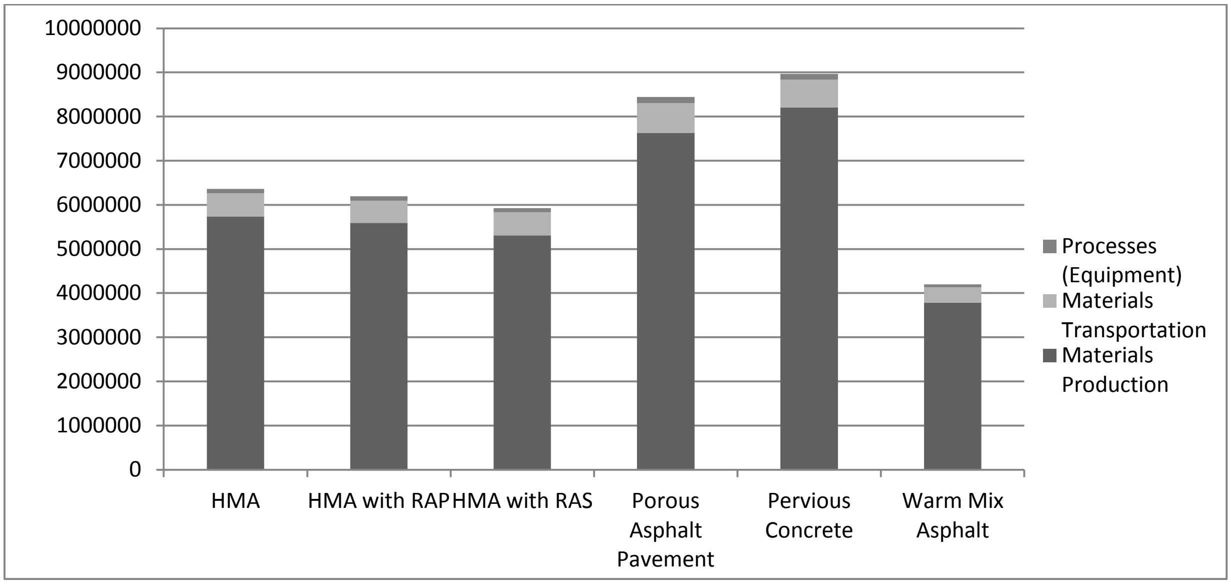


Figure D.1 – Initial Construction Energy Consumption (Industrial)

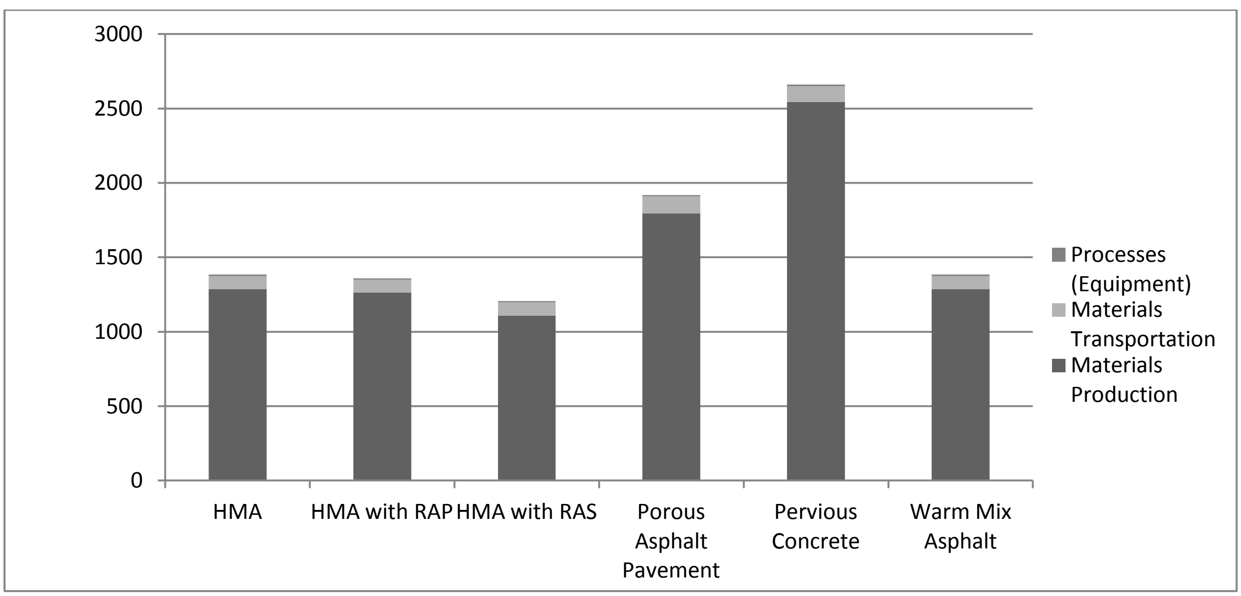


Figure D.2 – Initial Construction Water Consumption (Industrial)

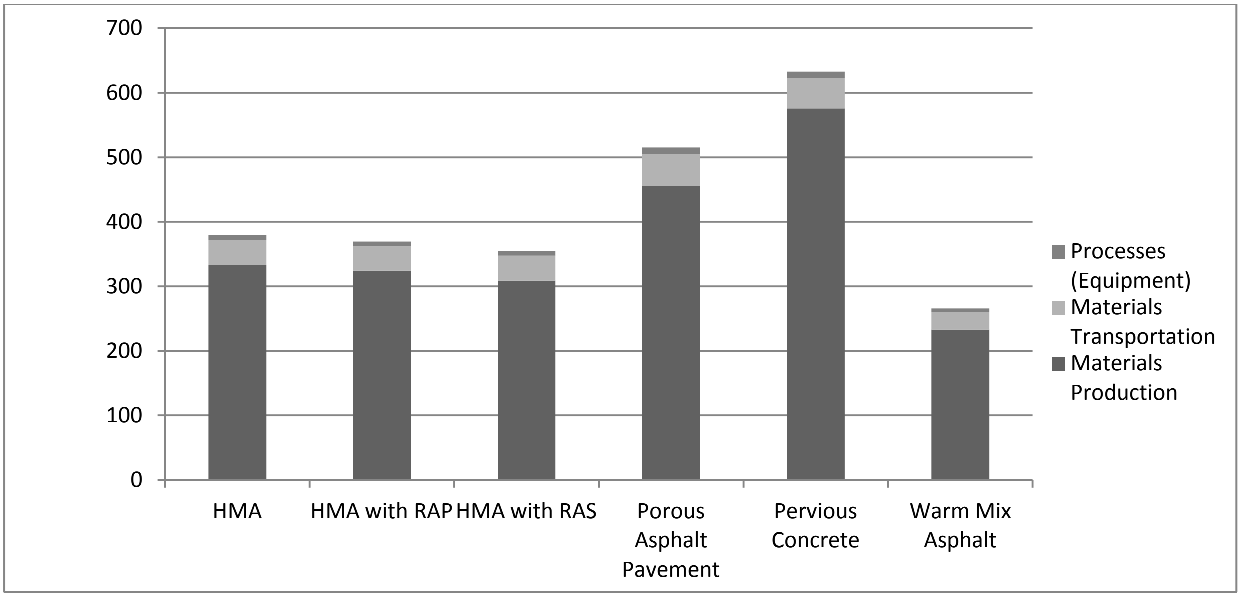


Figure D.3 – Initial Construction Carbon Dioxide Emissions (Industrial)

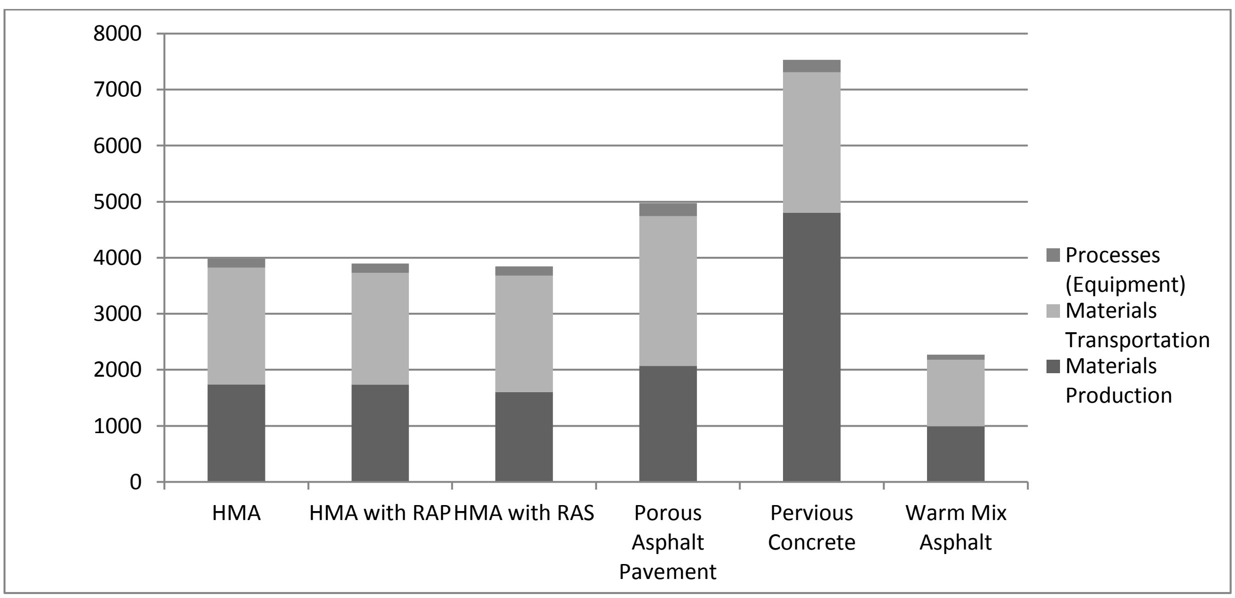


Figure D.4 – Initial Construction Nitrous Oxide Emissions (Industrial)

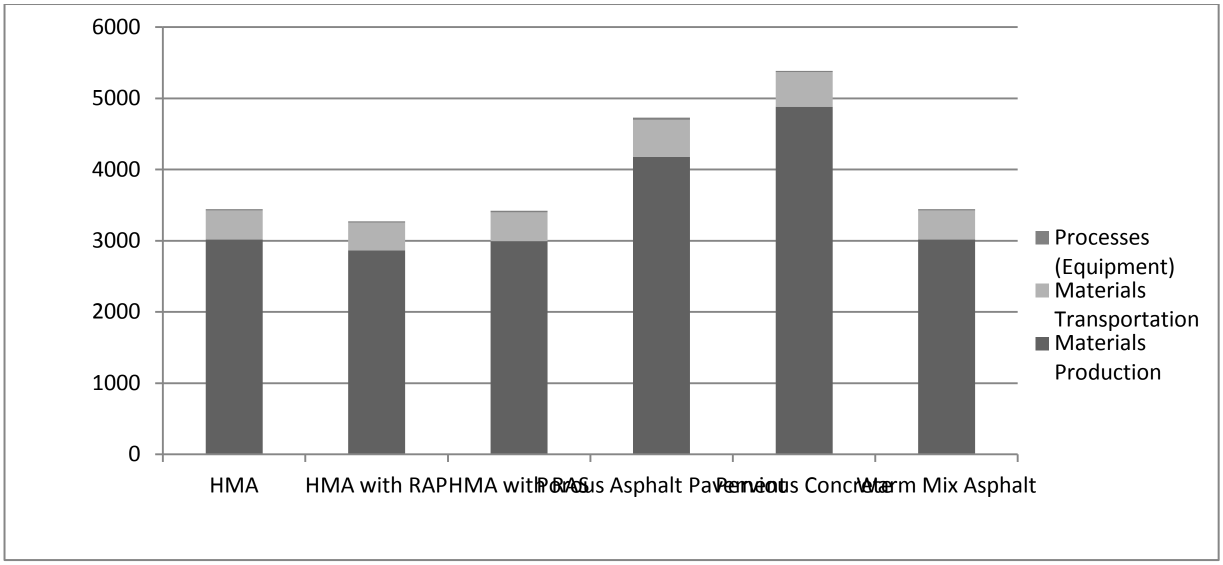


Figure D.5 – Initial Construction Particulate Matter 10 Emissions (Industrial)

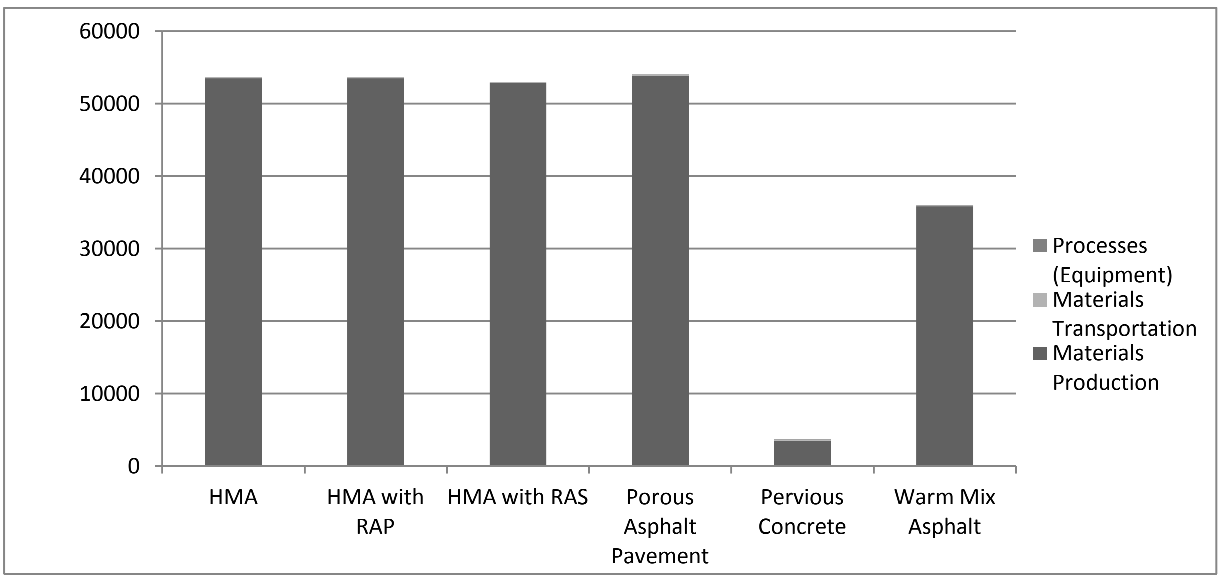


Figure D.6 – Initial Construction Sulphur Dioxide Emissions (Industrial)

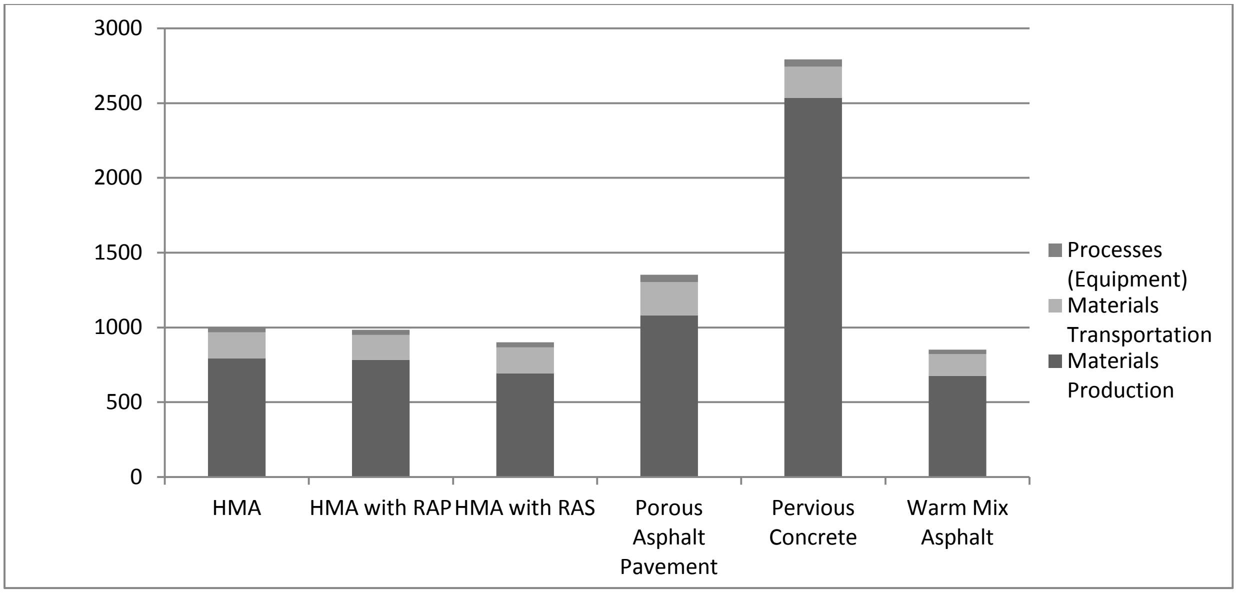


Figure D.7 – Initial Construction Carbon Monoxide Emissions (Industrial)

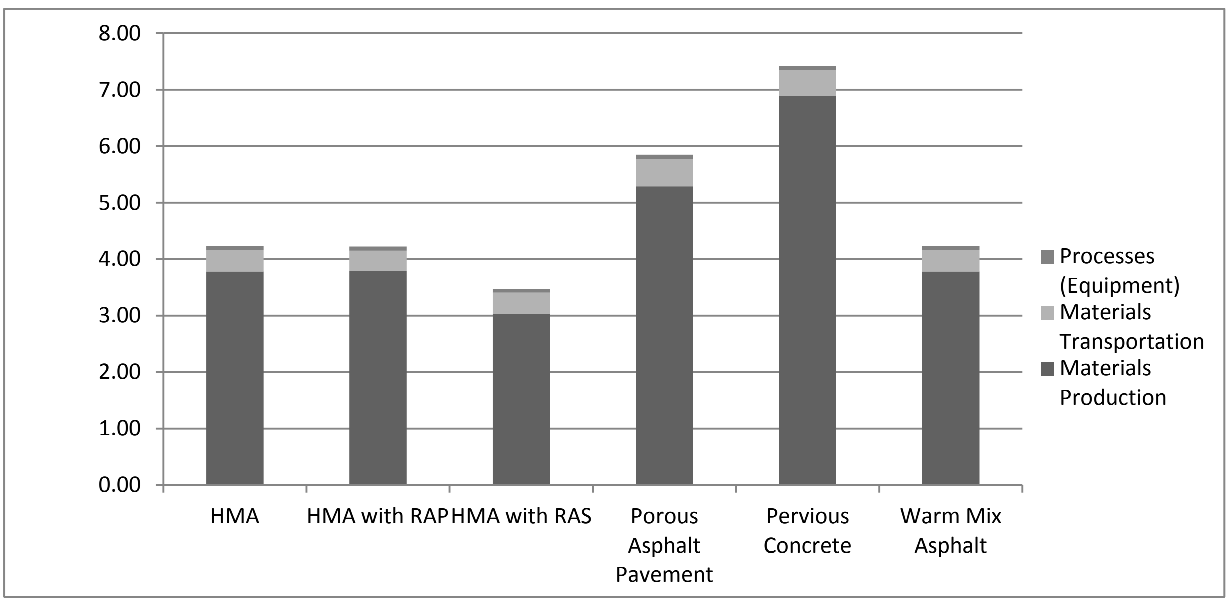


Figure D.8 – Initial Construction Mercury Emissions (Industrial)

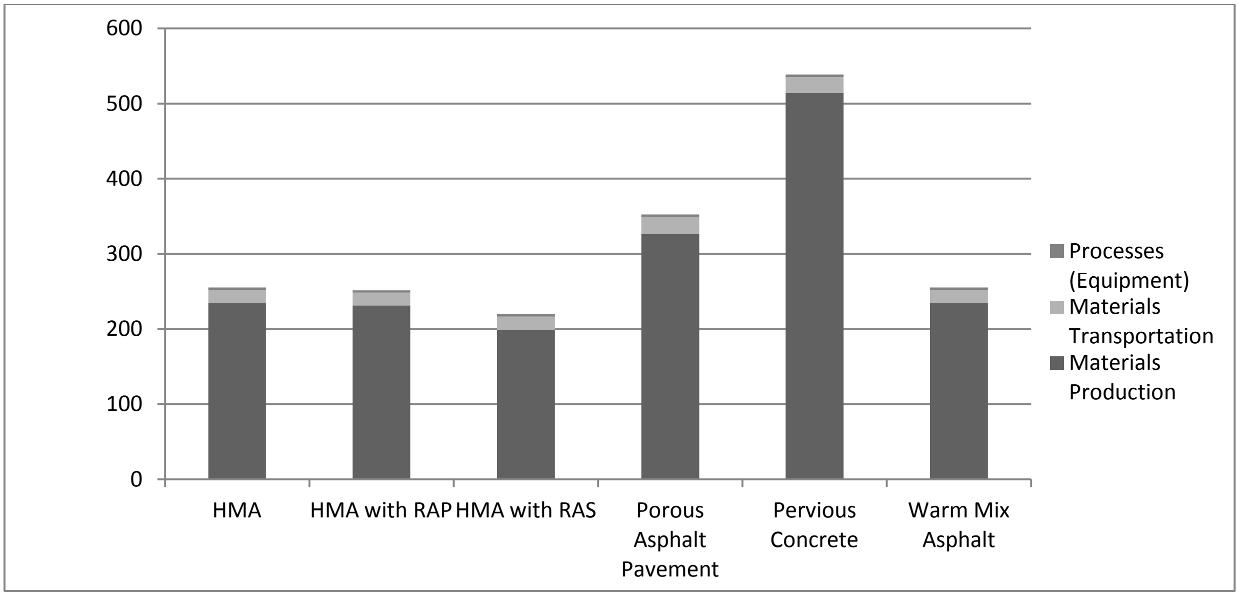


Figure D.9 – Initial Construction Lead Emissions (Industrial)

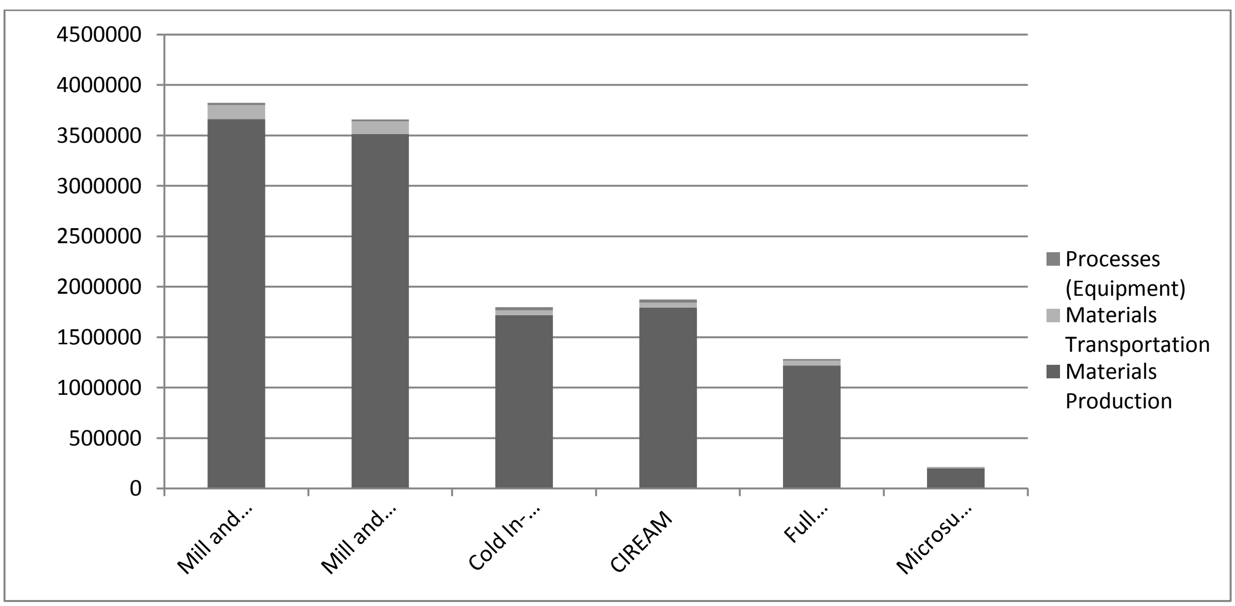


Figure D.10 – Rehabilitation Energy Consumption (Industrial)

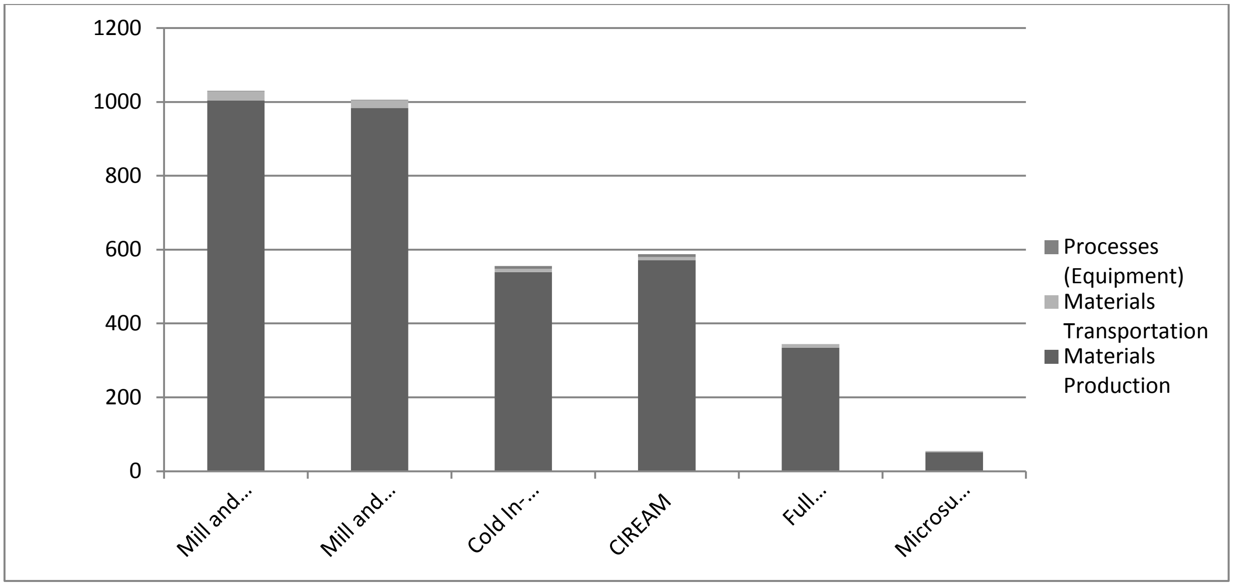


Figure D.11 – Rehabilitation Water Consumption (Industrial)

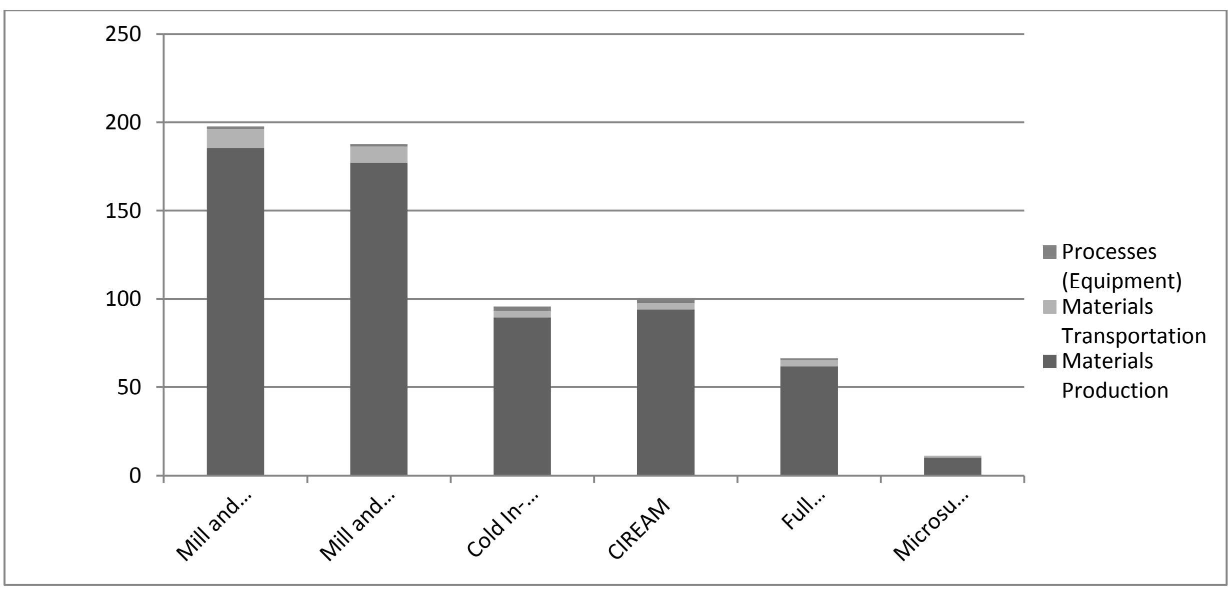


Figure D.12 – Rehabilitation Carbon Dioxide Emissions (Industrial)

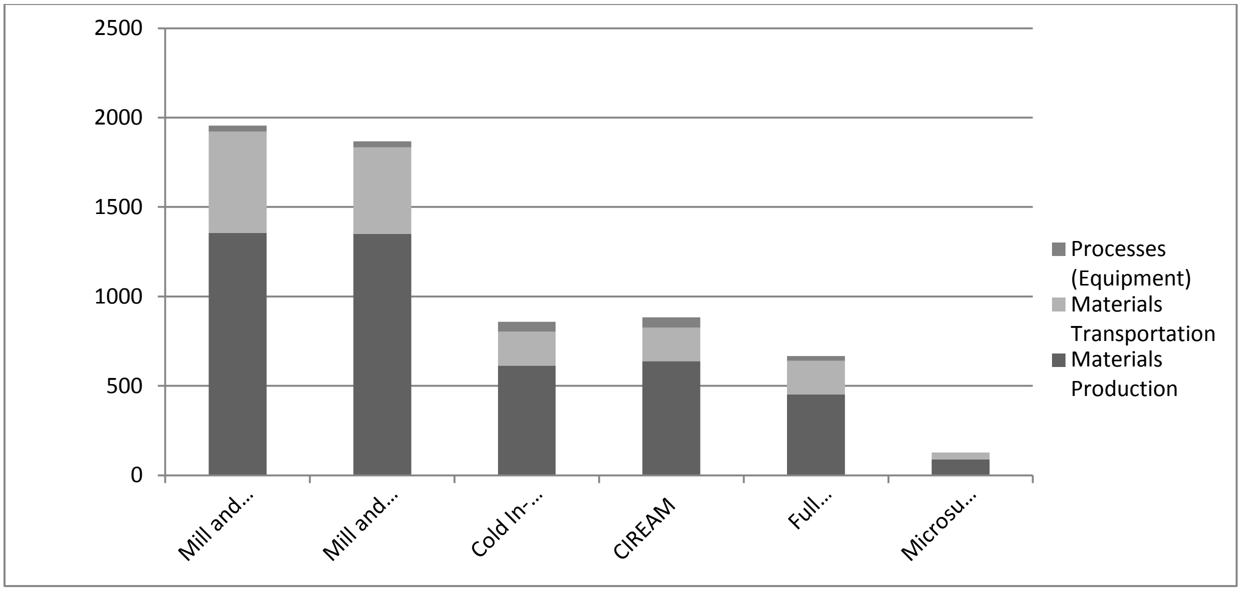


Figure D.13 – Rehabilitation Nitrous Oxide Emissions (Industrial)

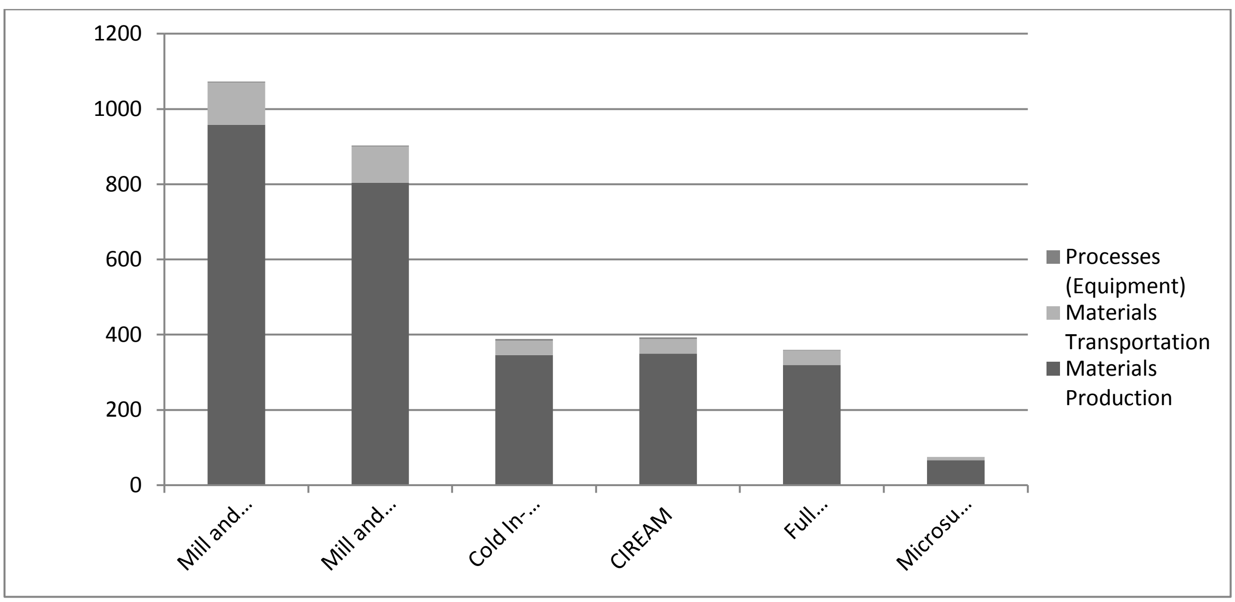


Figure D.14 – Rehabilitation Particulate Matter 10 Emissions (Industrial)

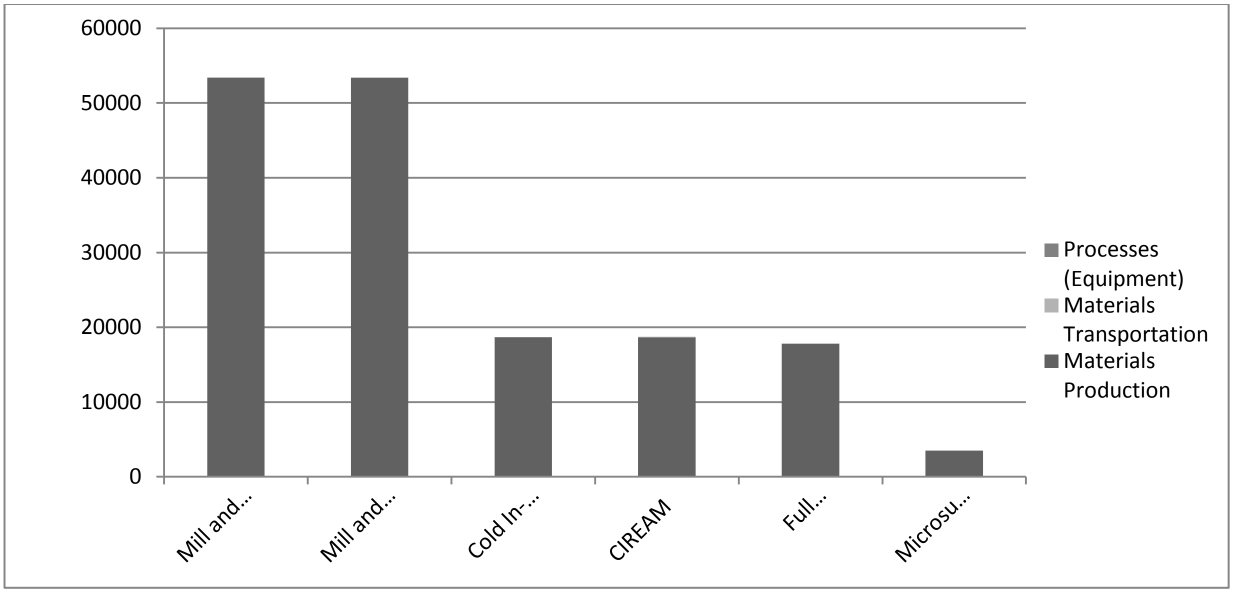


Figure D.15 – Rehabilitation Sulphur Dioxide Emissions (Industrial)

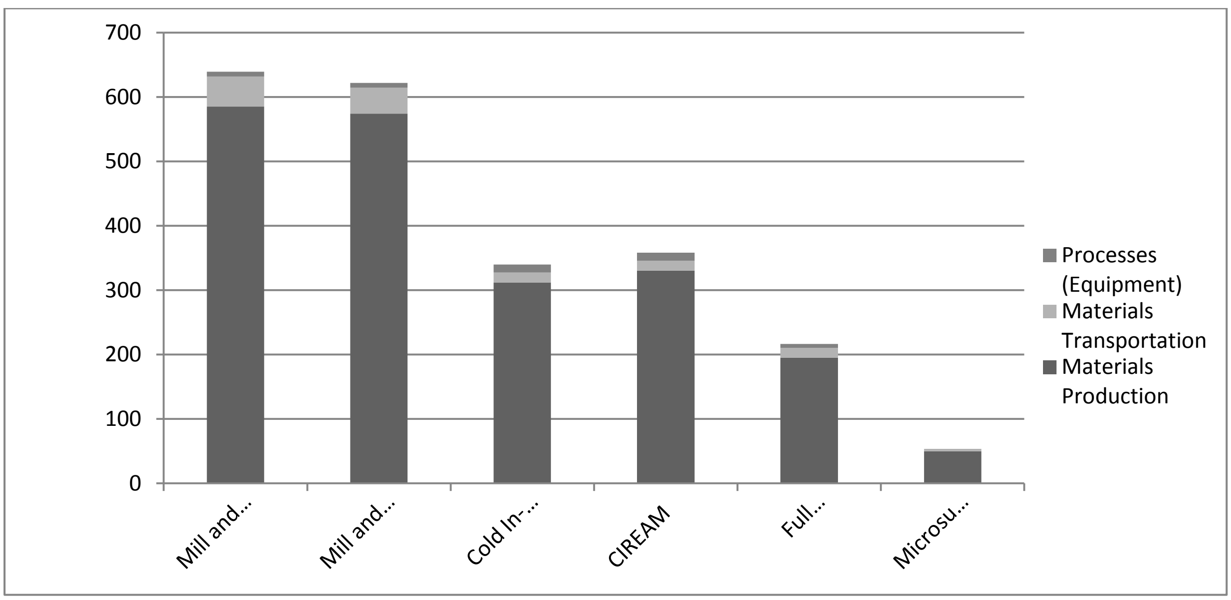


Figure D.16 – Rehabilitation Carbon Monoxide Emissions (Industrial)

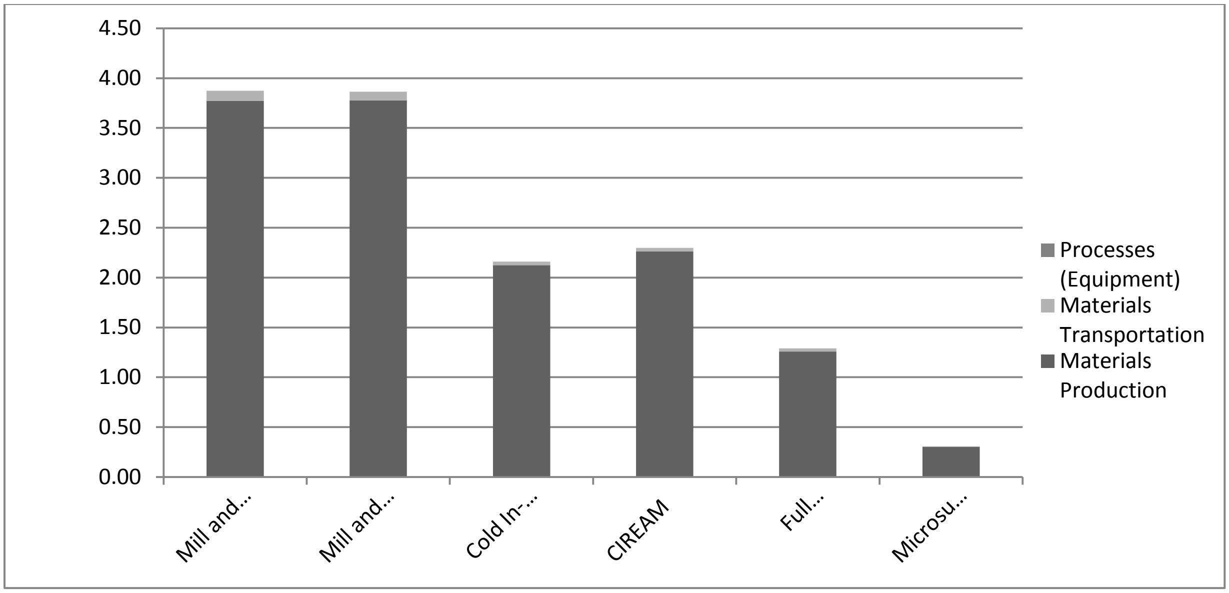


Figure D.17 – Rehabilitation Mercury Emissions (Industrial)

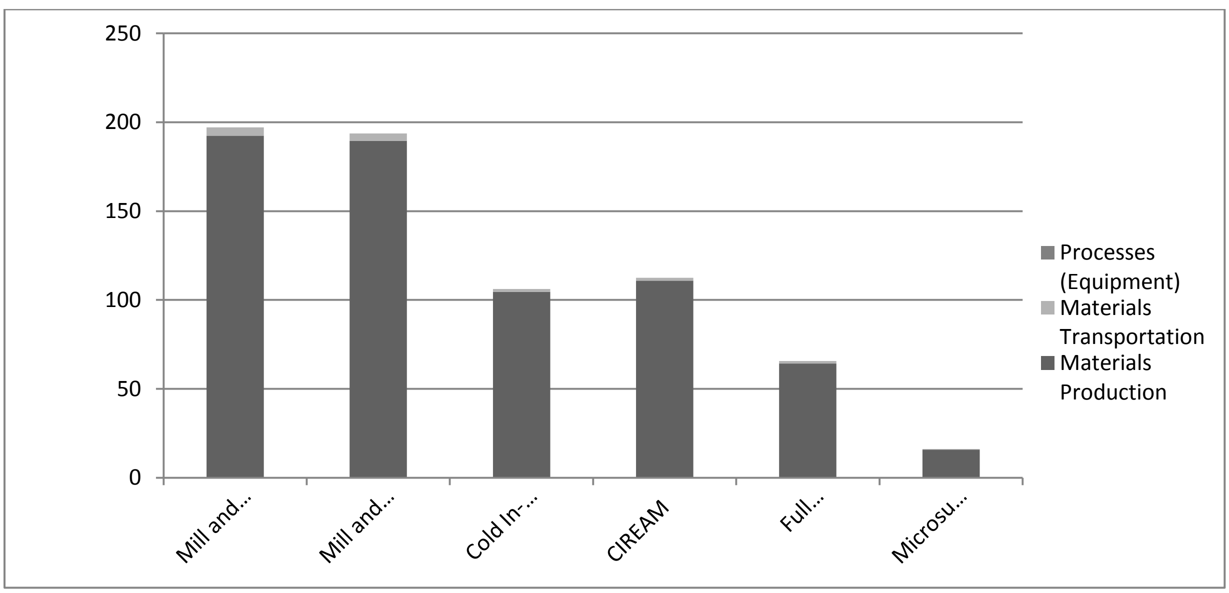


Figure D.18 – Rehabilitation Lead Emissions (Industrial)

OUTPUT – Graphical (Laneway)

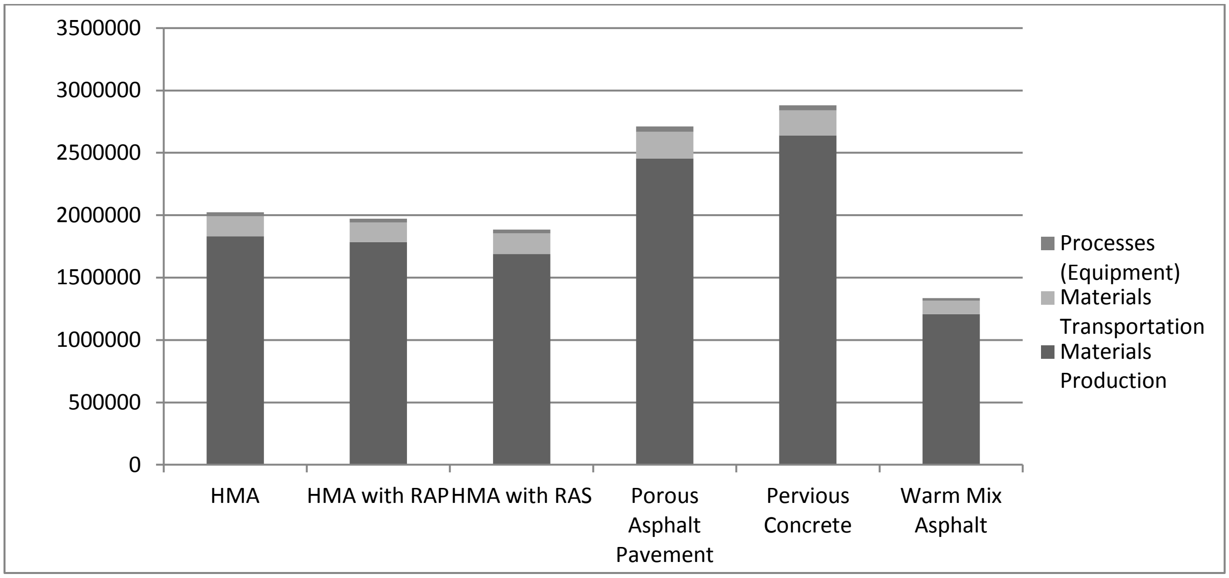


Figure D.19 – Initial Construction Energy Consumption (Laneway)

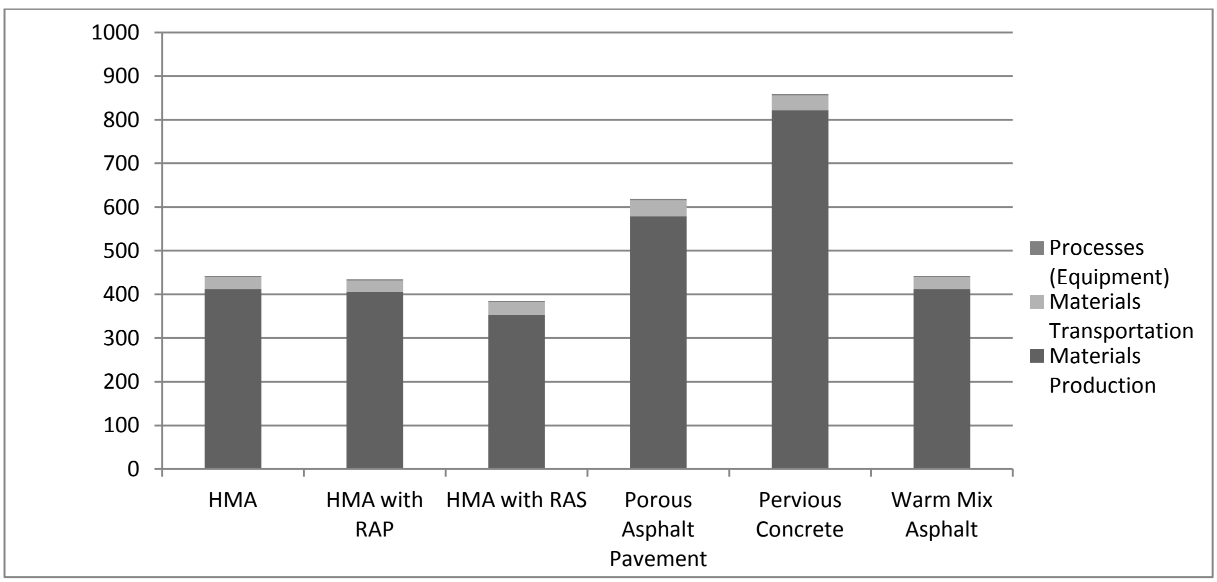


Figure D.20 – Initial Construction Water Consumption (Laneway)

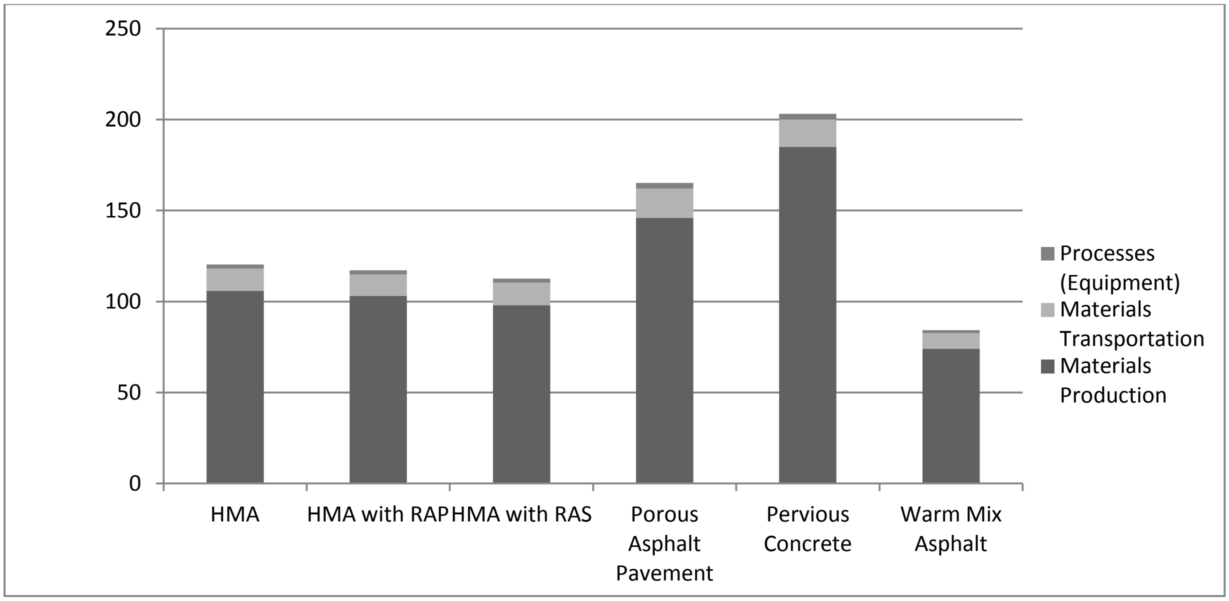


Figure D.21 – Initial Construction Carbon Dioxide Emissions (Laneway)

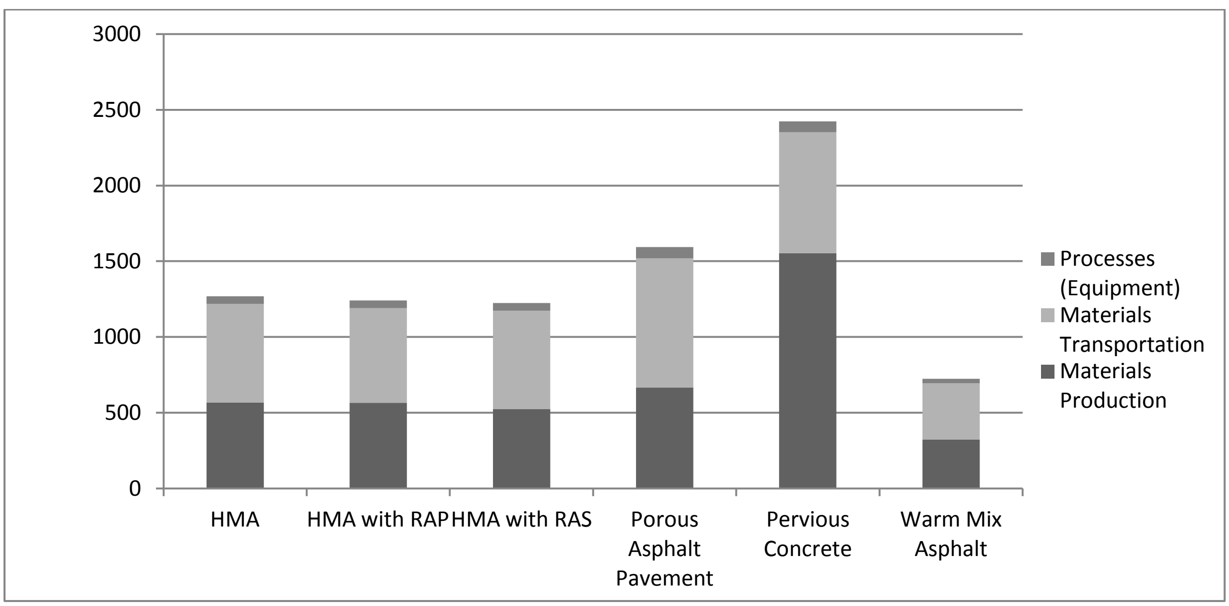


Figure D.22 – Initial Construction Nitrous Oxide Emissions (Laneway)

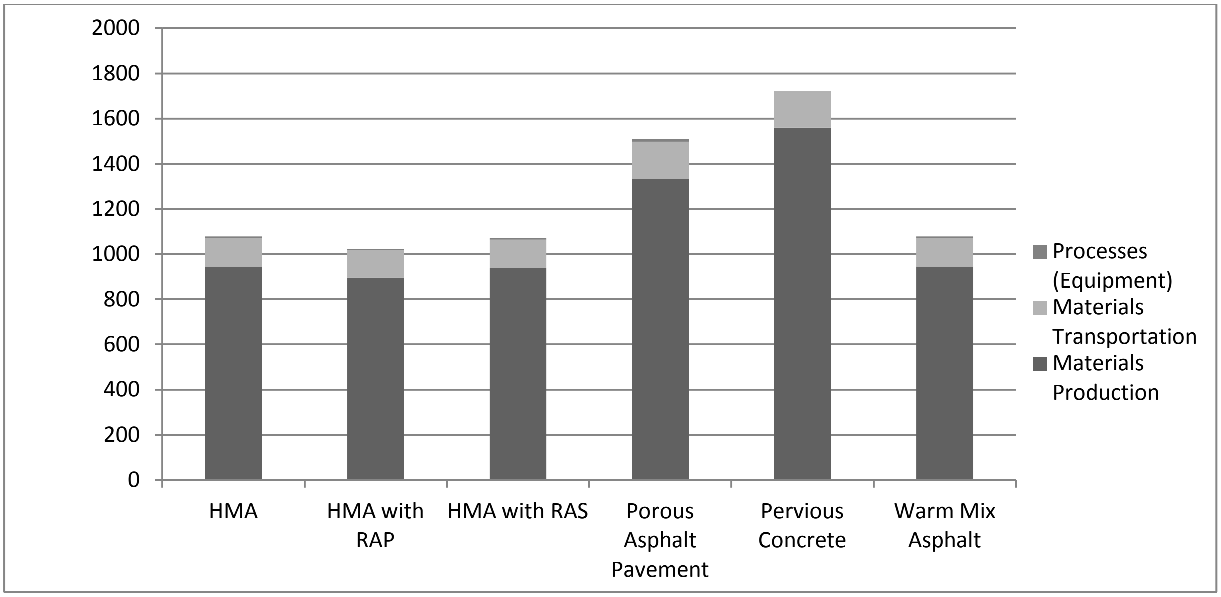


Figure D.23 – Initial Construction Particulate Matter 10 Emissions (Laneway)

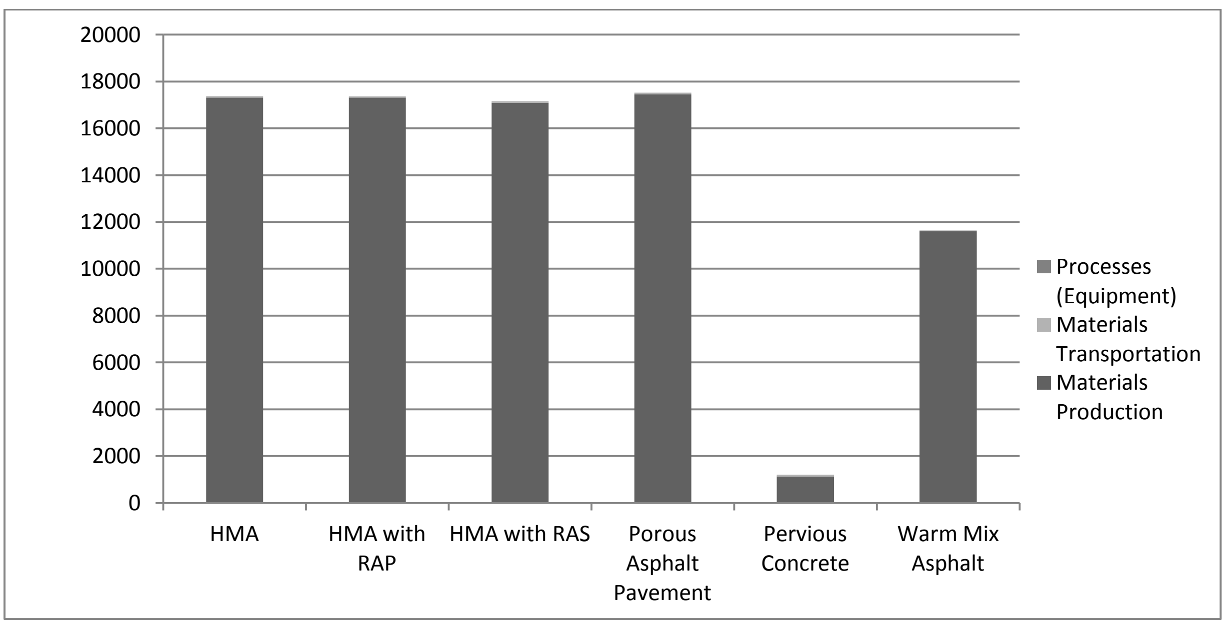


Figure D.24 – Initial Construction Sulphur Dioxide Emissions (Laneway)

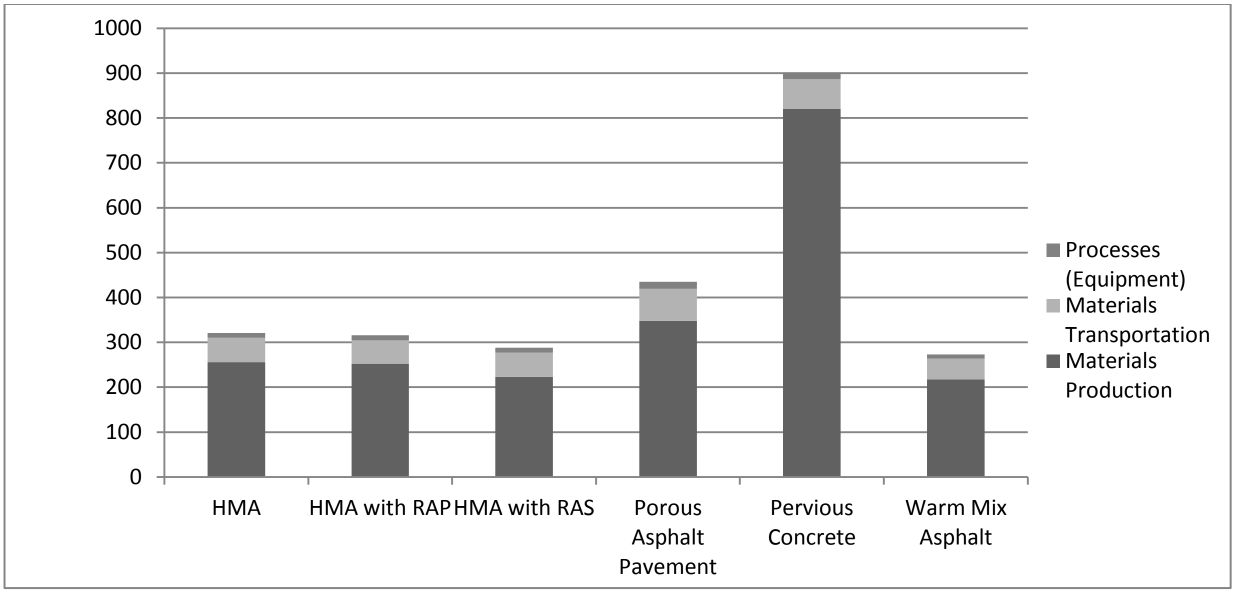


Figure D.25 – Initial Construction Carbon Monoxide Emissions (Laneway)

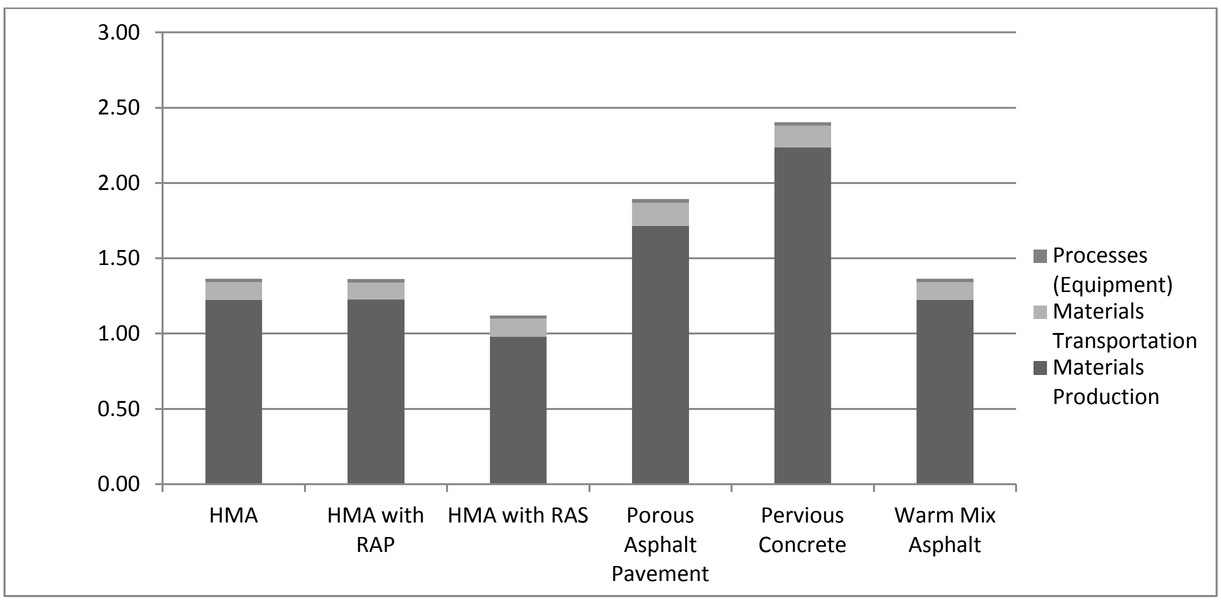


Figure D.26 – Initial Construction Mercury Emissions (Laneway)

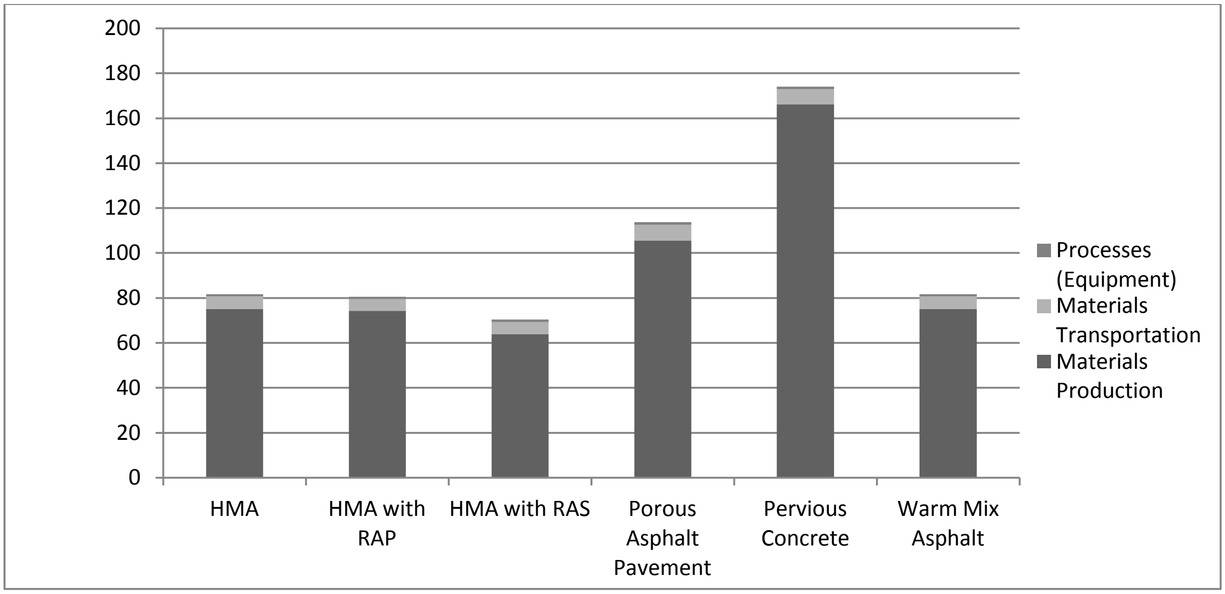


Figure D.27 – Initial Construction Lead Emissions (Laneway)

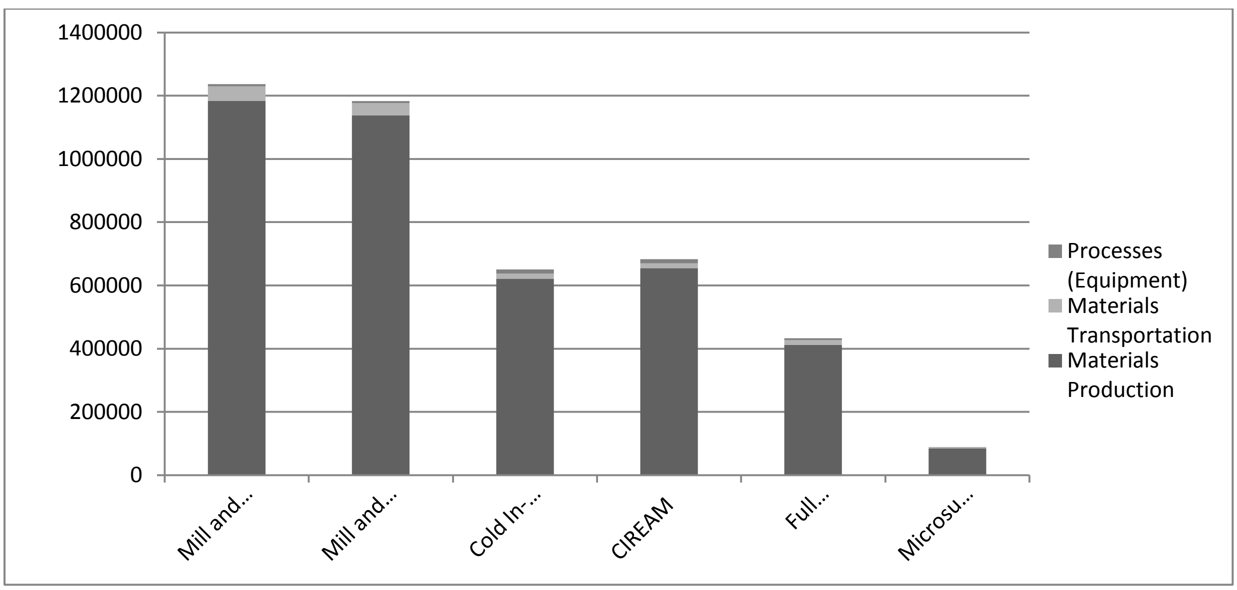


Figure D.28 – Rehabilitation Energy Consumption (Laneway)

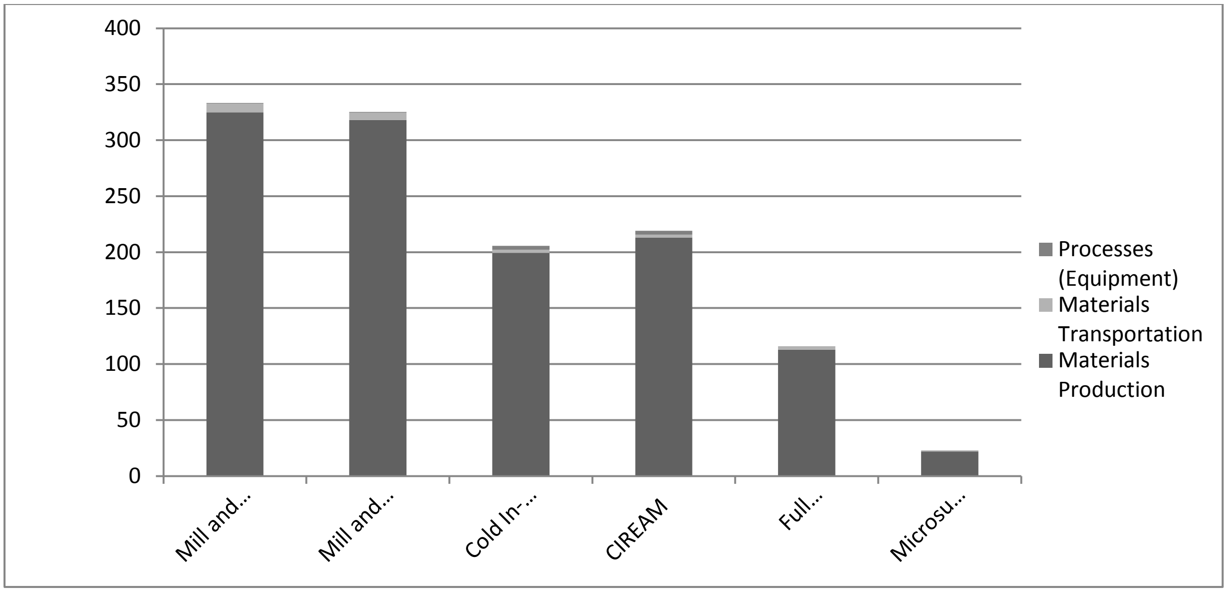


Figure D.29 – Rehabilitation Water Consumption (Laneway)

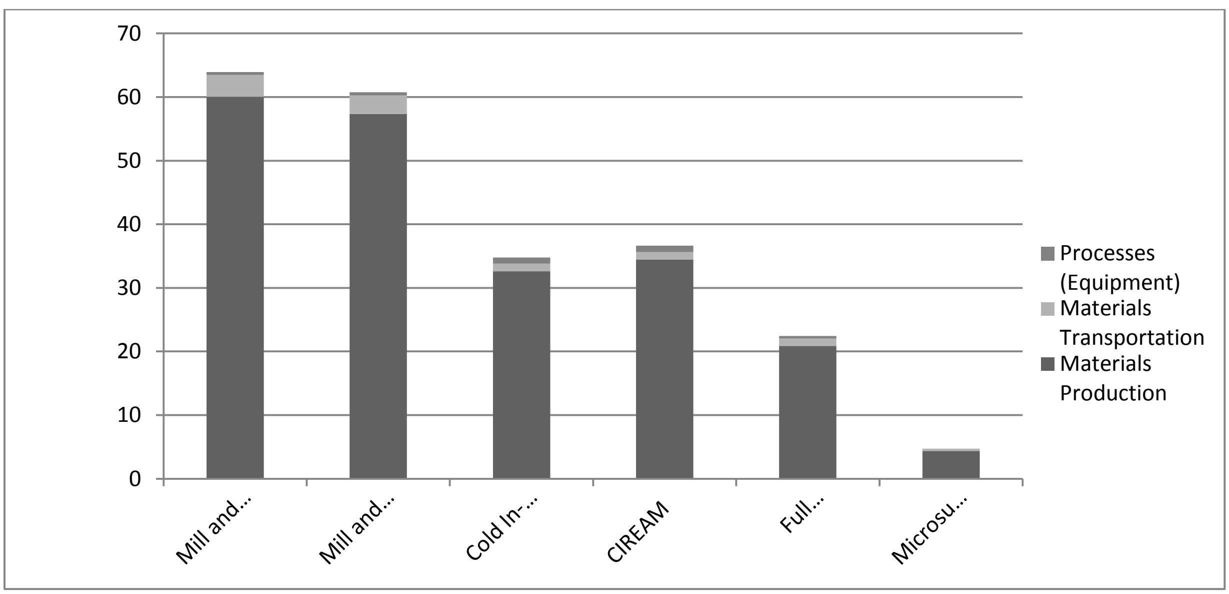


Figure D.30 – Rehabilitation Carbon Dioxide Emissions (Laneway)

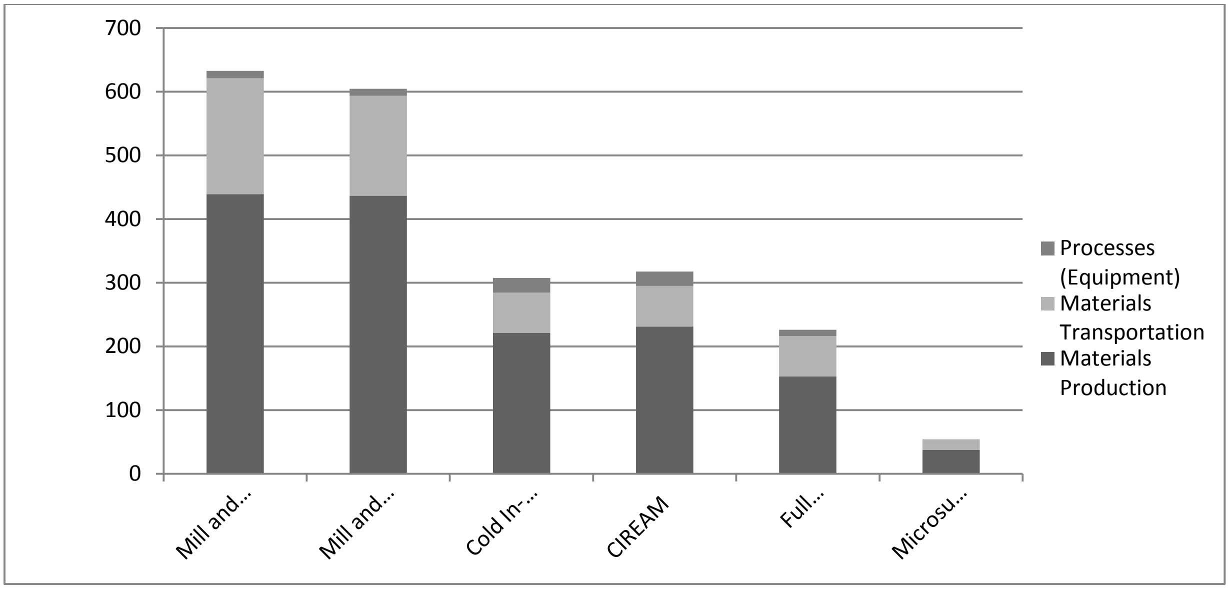


Figure D.31 – Rehabilitation Nitrous Oxide Emissions (Laneway)

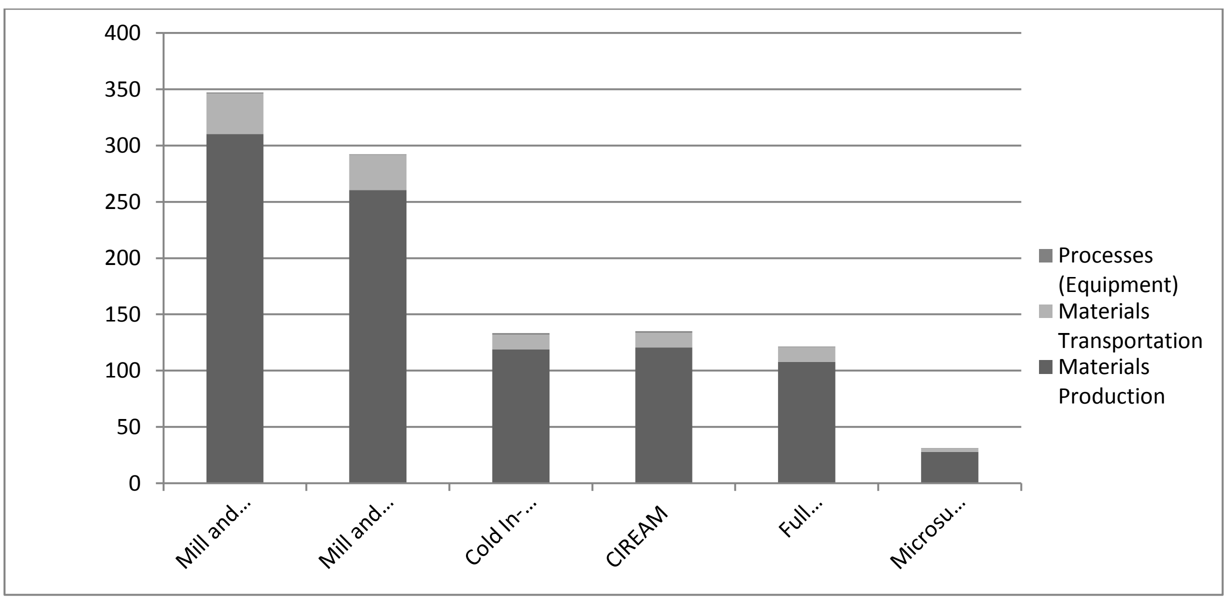


Figure D.32 – Rehabilitation Particulate Matter 10 Emissions (Laneway)

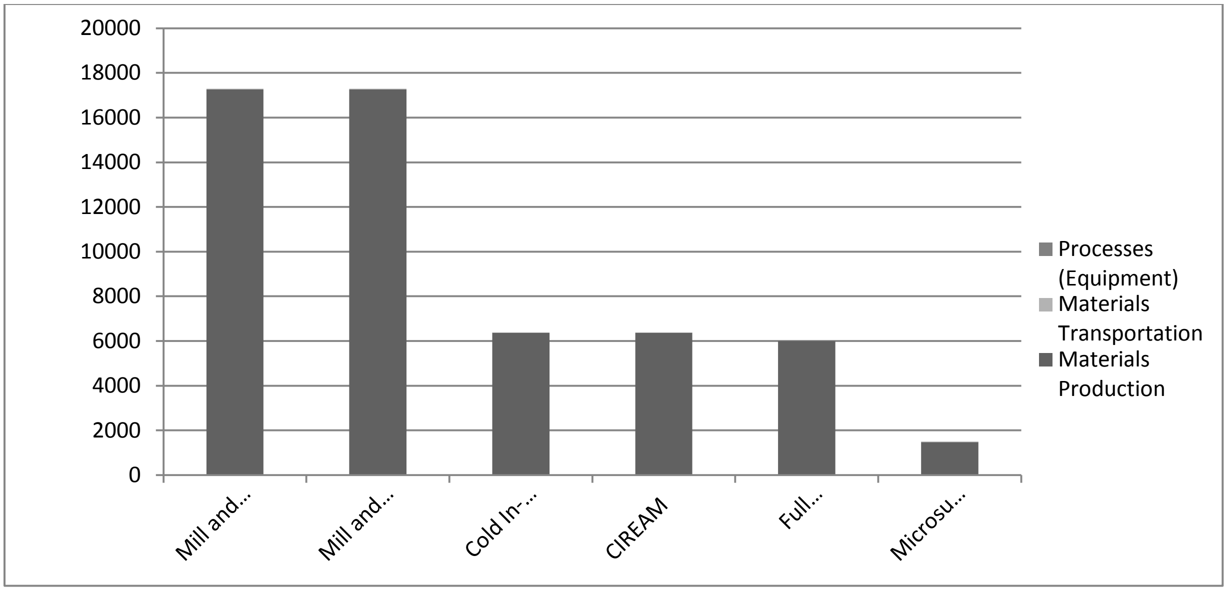


Figure D.33 – Rehabilitation Sulphur Dioxide Emissions (Laneway)

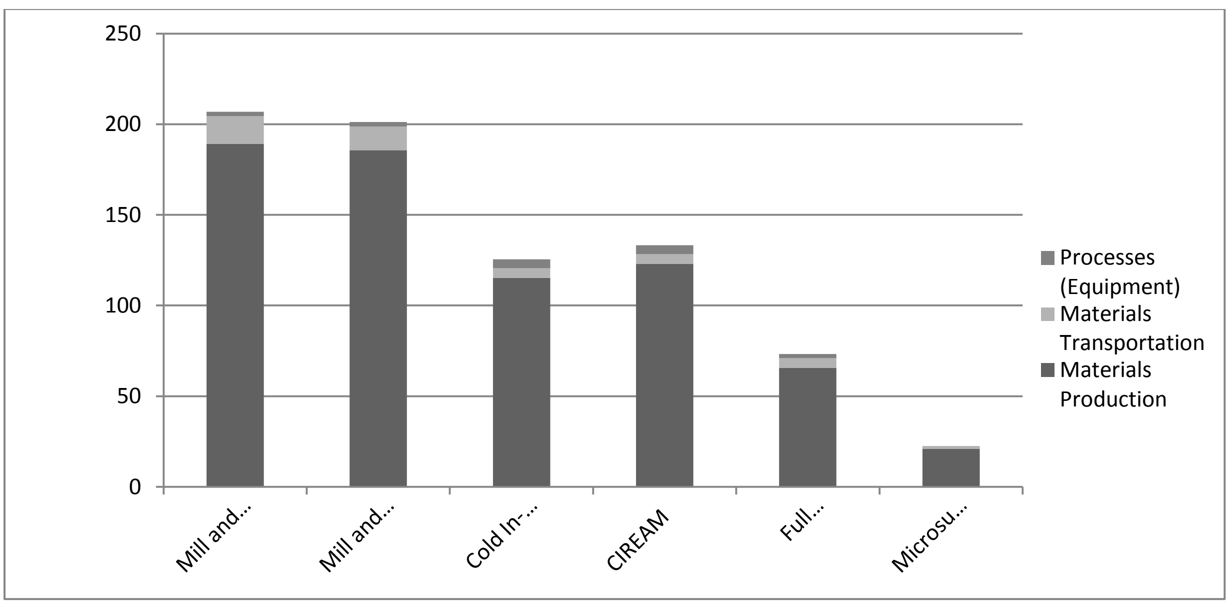


Figure D.34 – Rehabilitation Carbon Monoxide Emissions (Laneway)

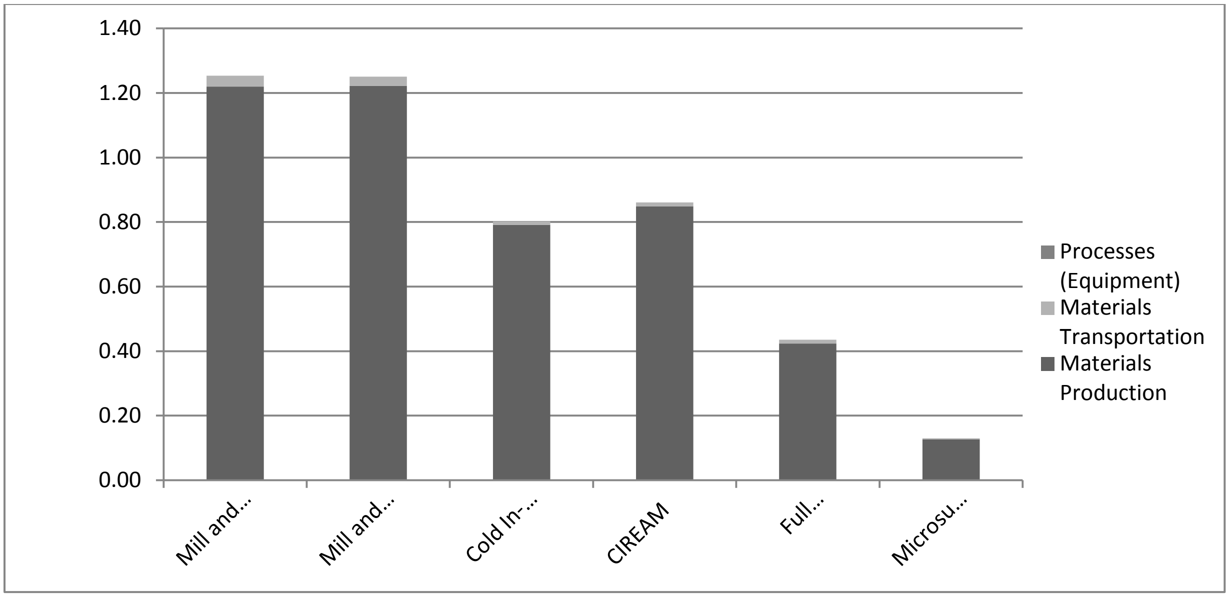


Figure D.35 – Rehabilitation Mercury Emissions (Laneway)

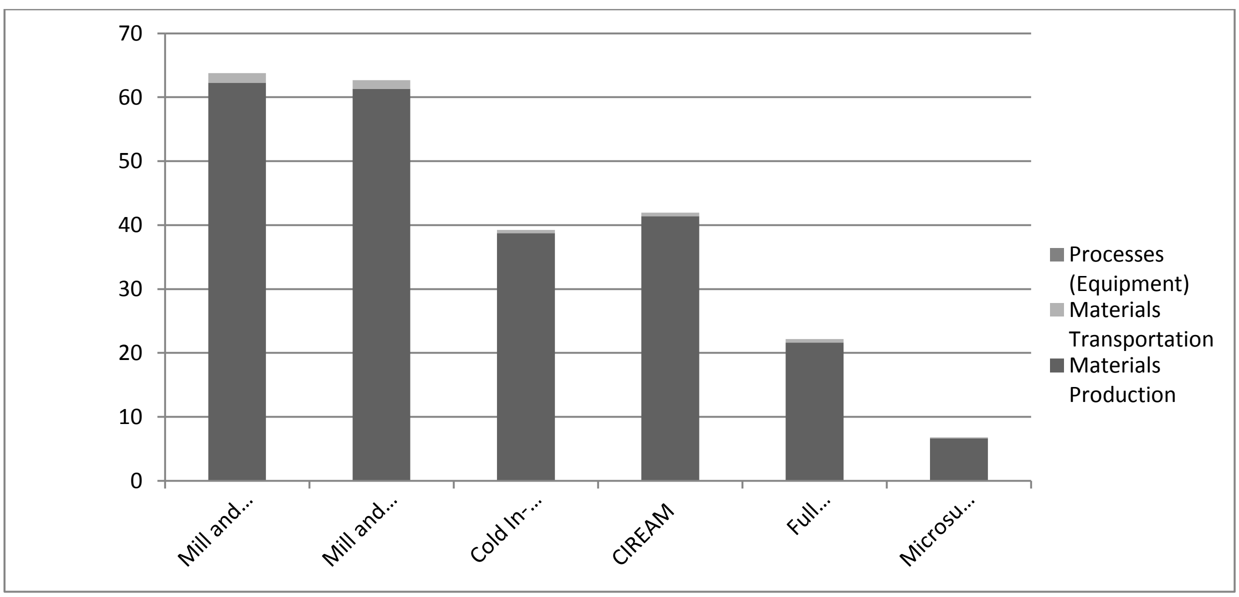


Figure D.36 – Rehabilitation Lead Emissions (Laneway)

OUTPUT – Graphical (Local)

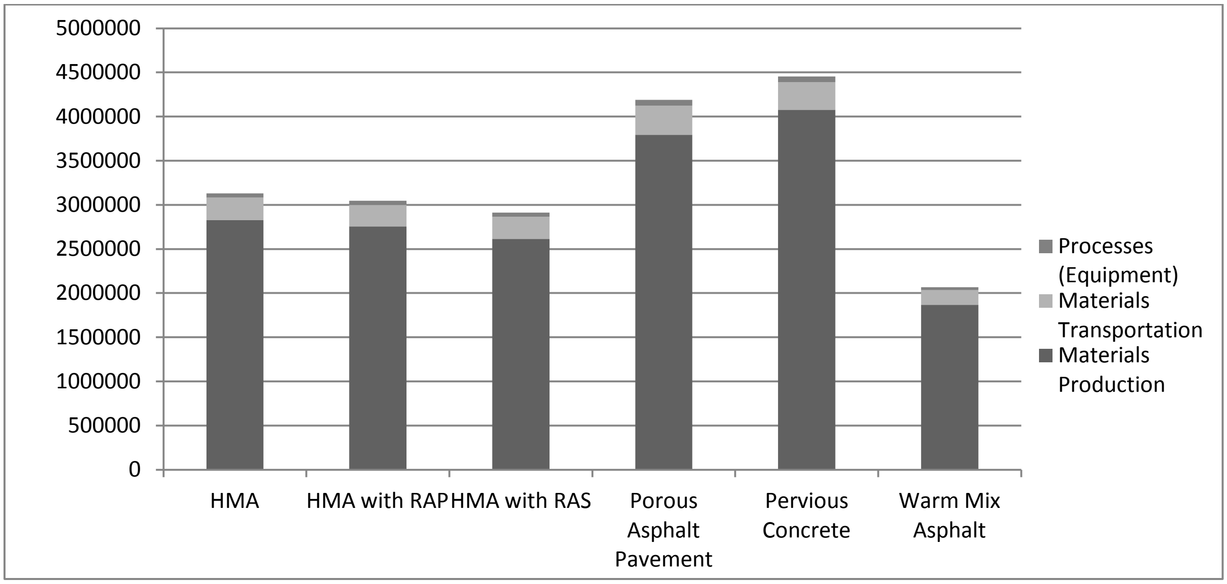


Figure D.37 – Initial Construction Energy Consumption (Local)

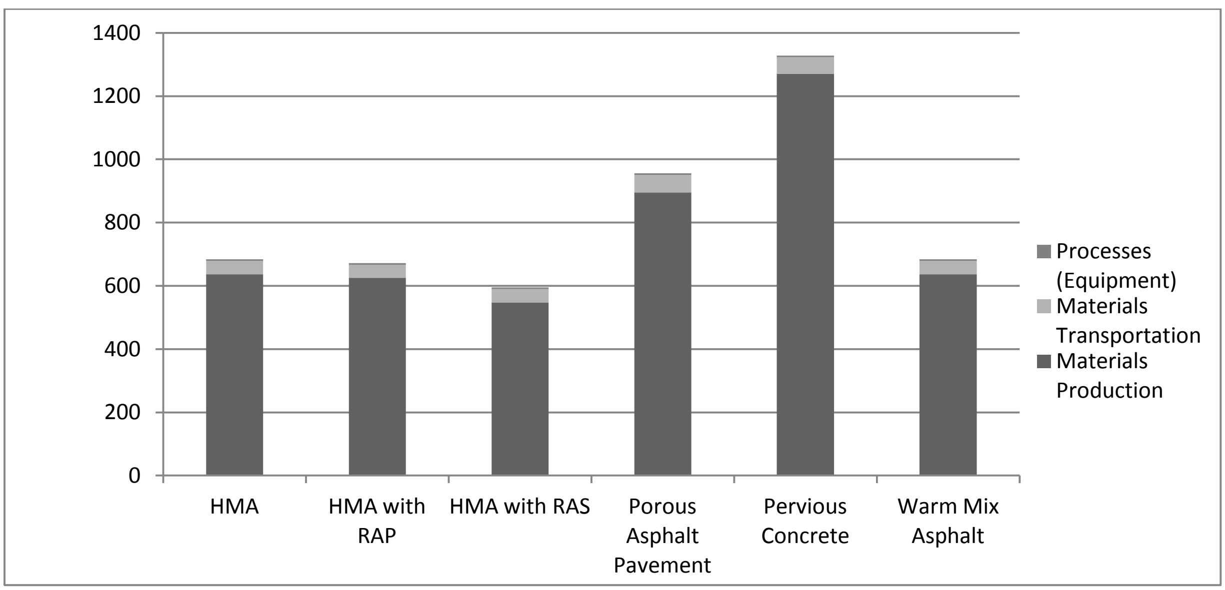


Figure D.38 – Initial Construction Water Consumption (Local)

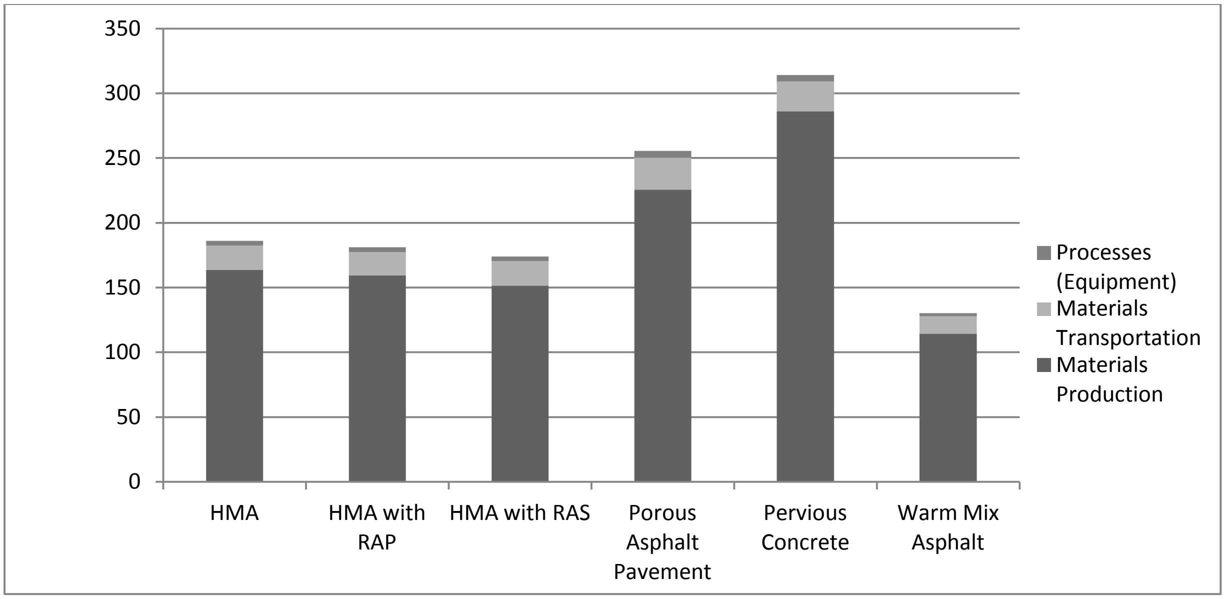


Figure D.39 – Initial Construction Carbon Dioxide Emissions (Local)

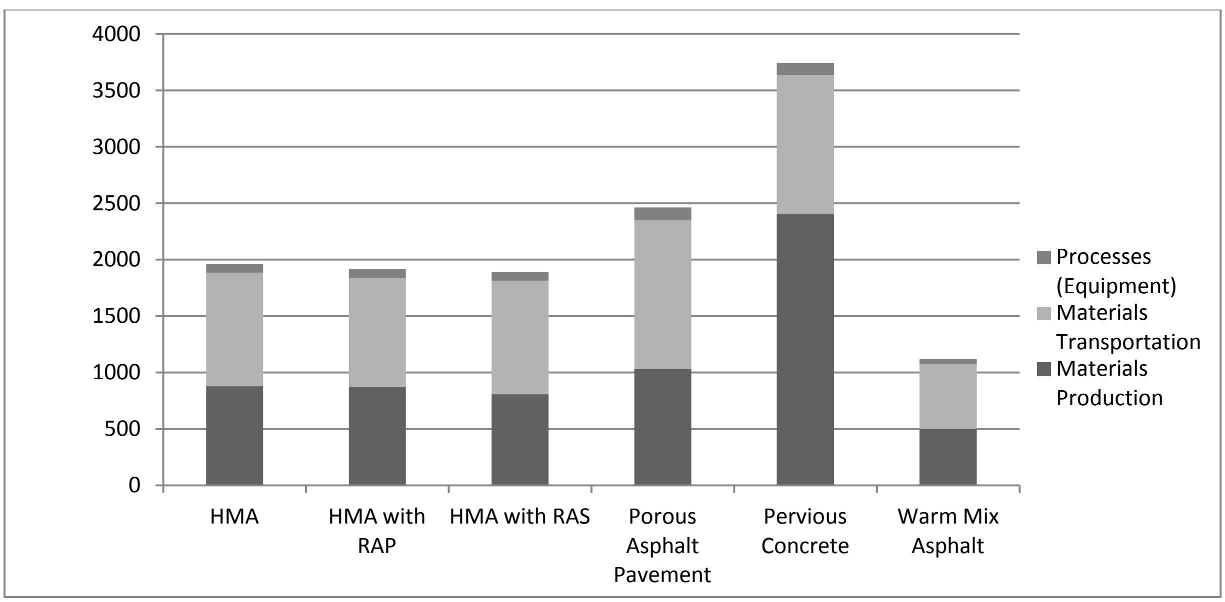


Figure D.40 – Initial Construction Nitrous Oxide Emissions (Local)

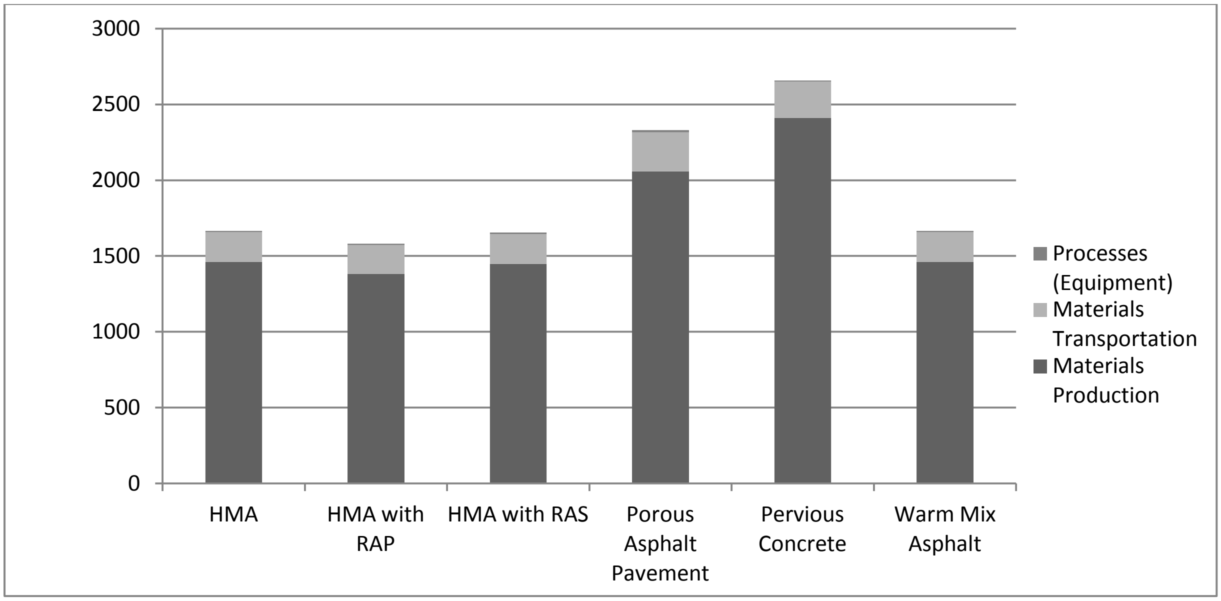


Figure D.41 – Initial Construction Particulate Matter 10 Emissions (Local)

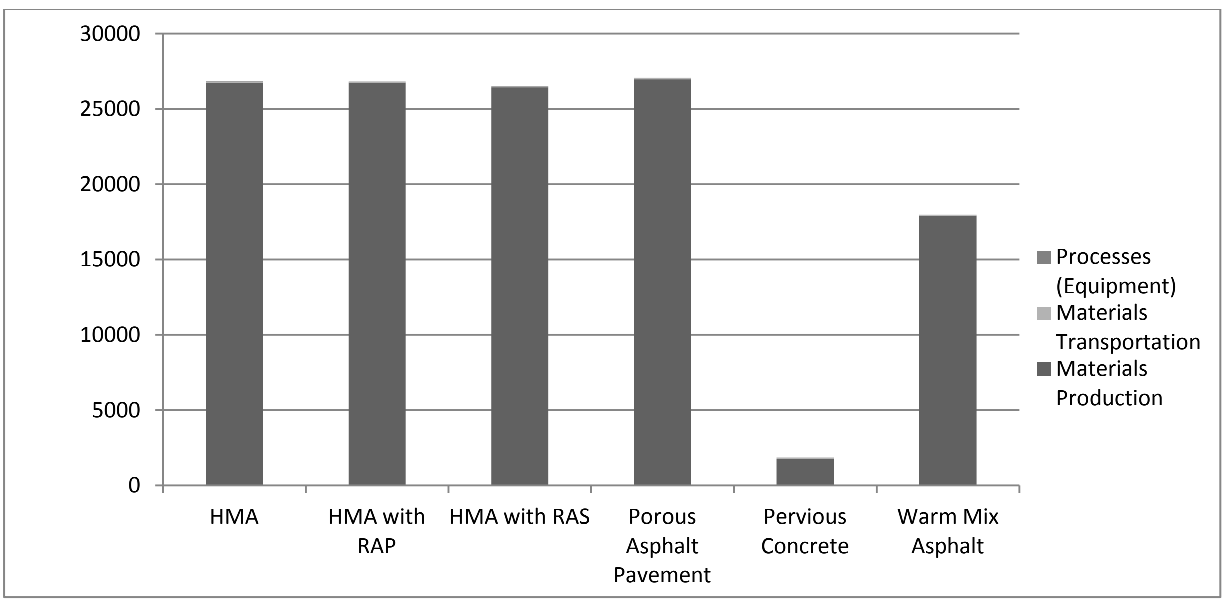


Figure D.42 – Initial Construction Sulphur Dioxide Emissions (Local)

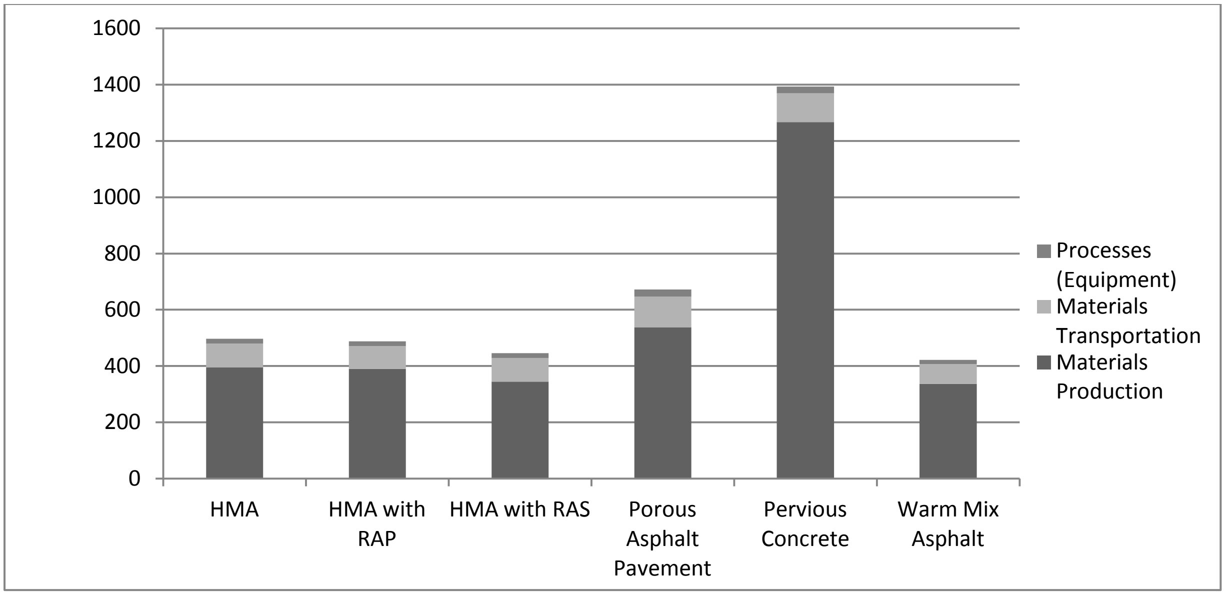


Figure D.43 – Initial Construction Carbon Monoxide Emissions (Local)

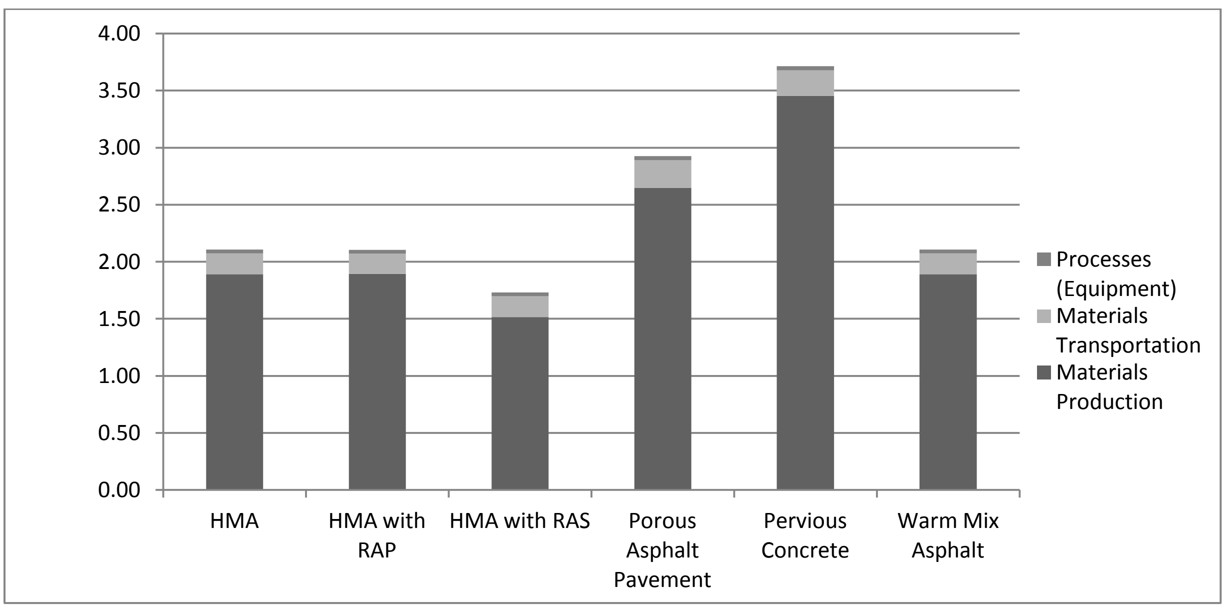


Figure D.44 – Initial Construction Mercury Emissions (Local)

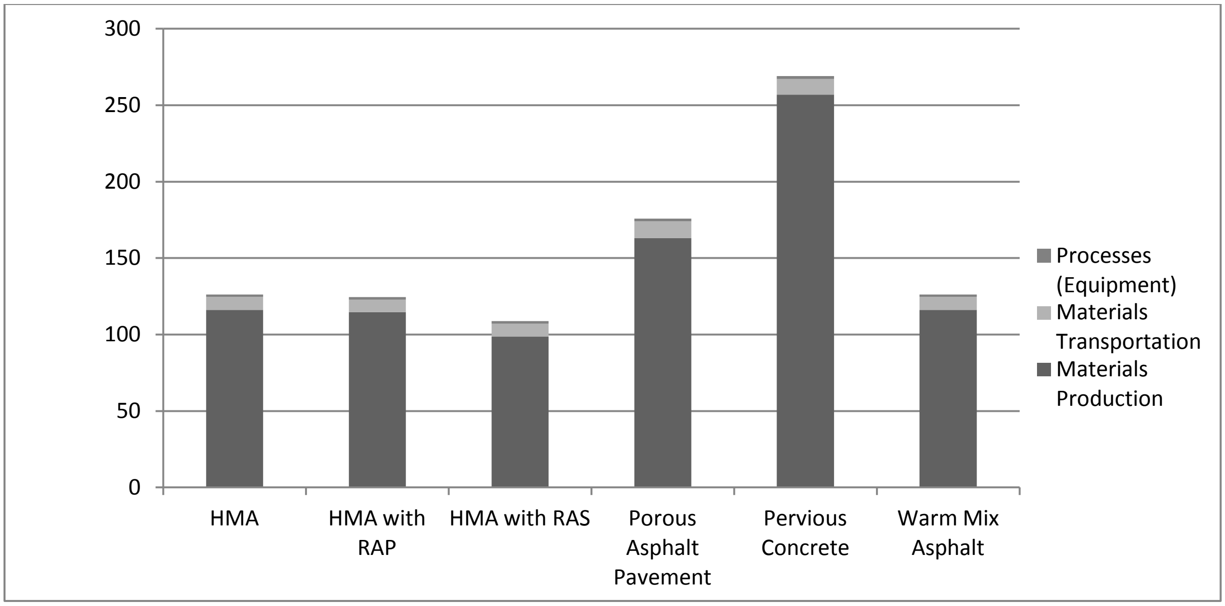


Figure D.45 – Initial Construction Lead Emissions (Local)

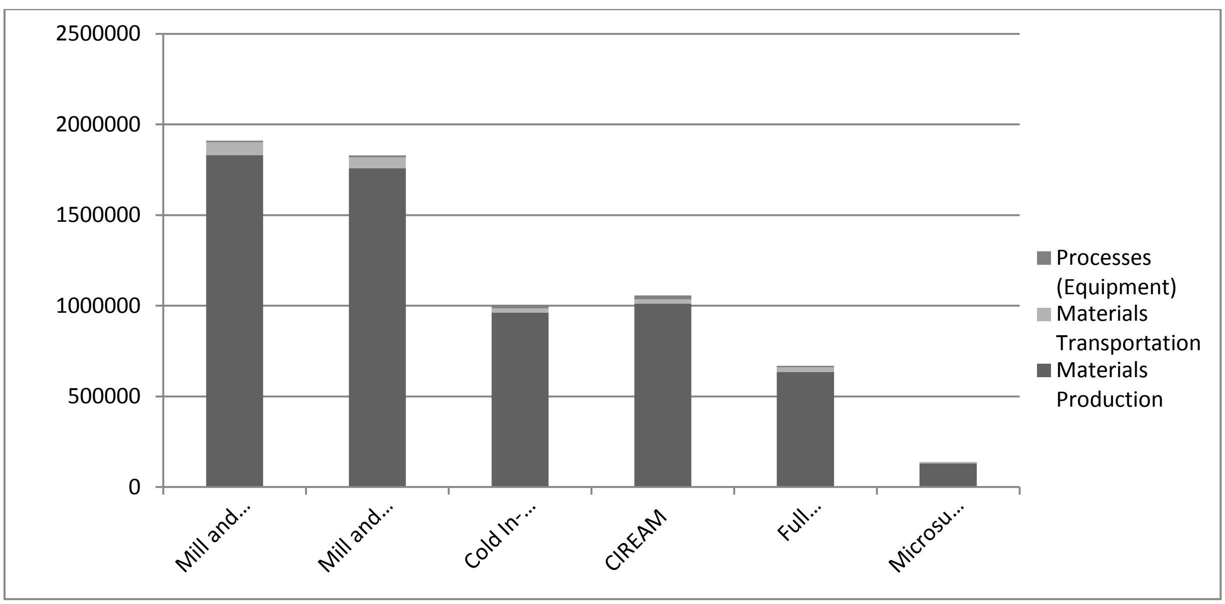


Figure D.46 – Rehabilitation Energy Consumption (Local)

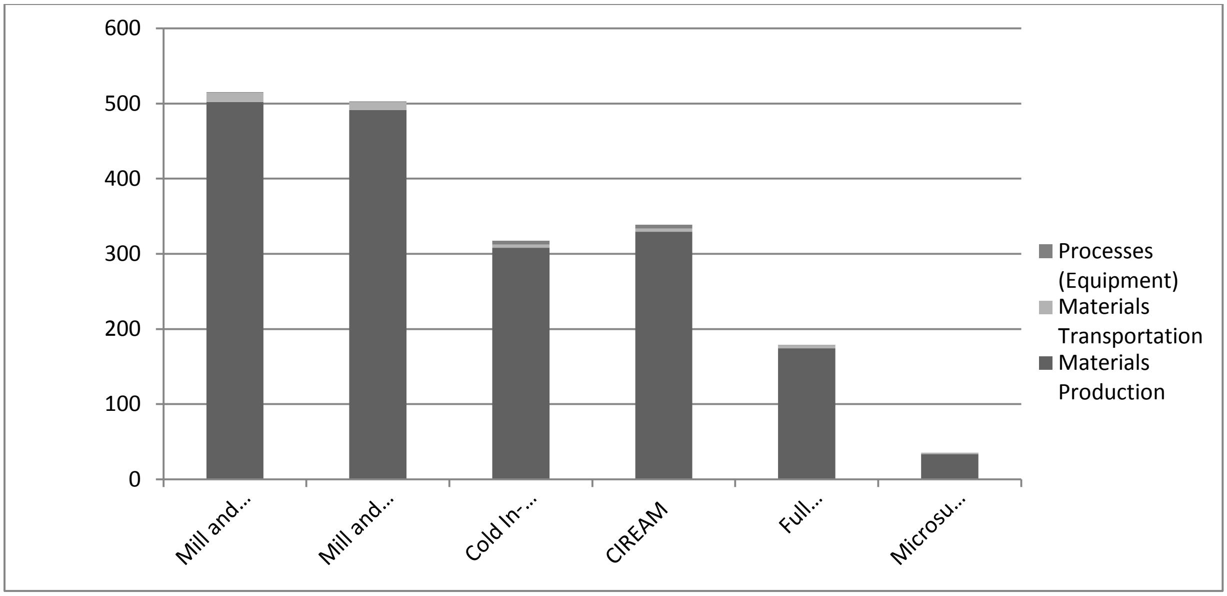


Figure D.47 – Rehabilitation Water Consumption (Local)

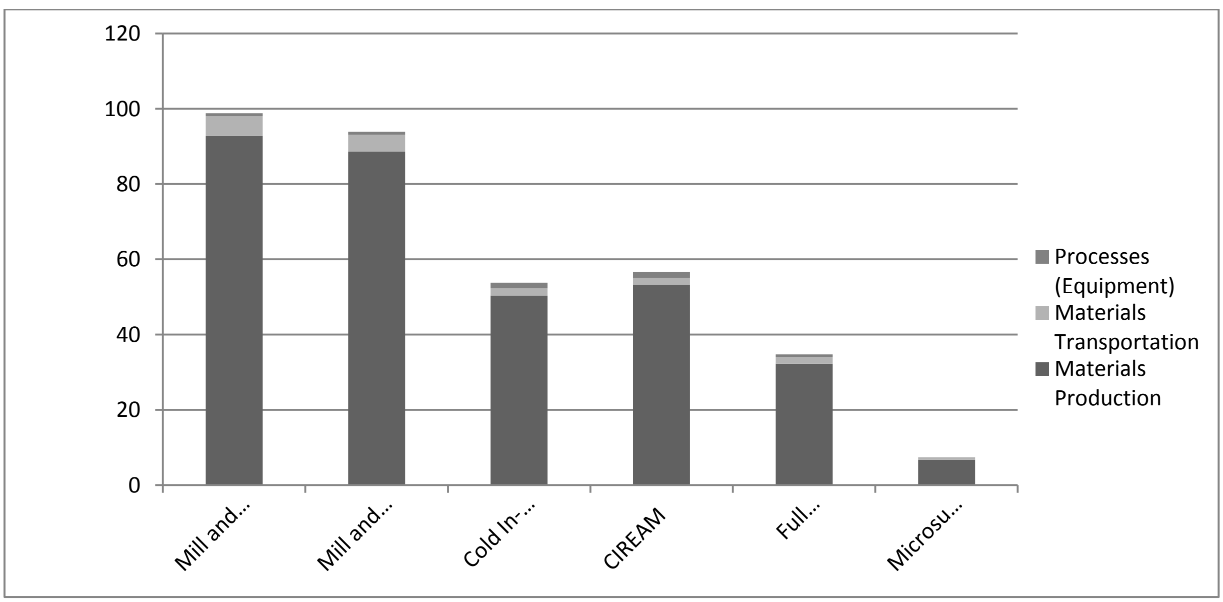


Figure D.48 – Rehabilitation Carbon Dioxide Emissions (Local)

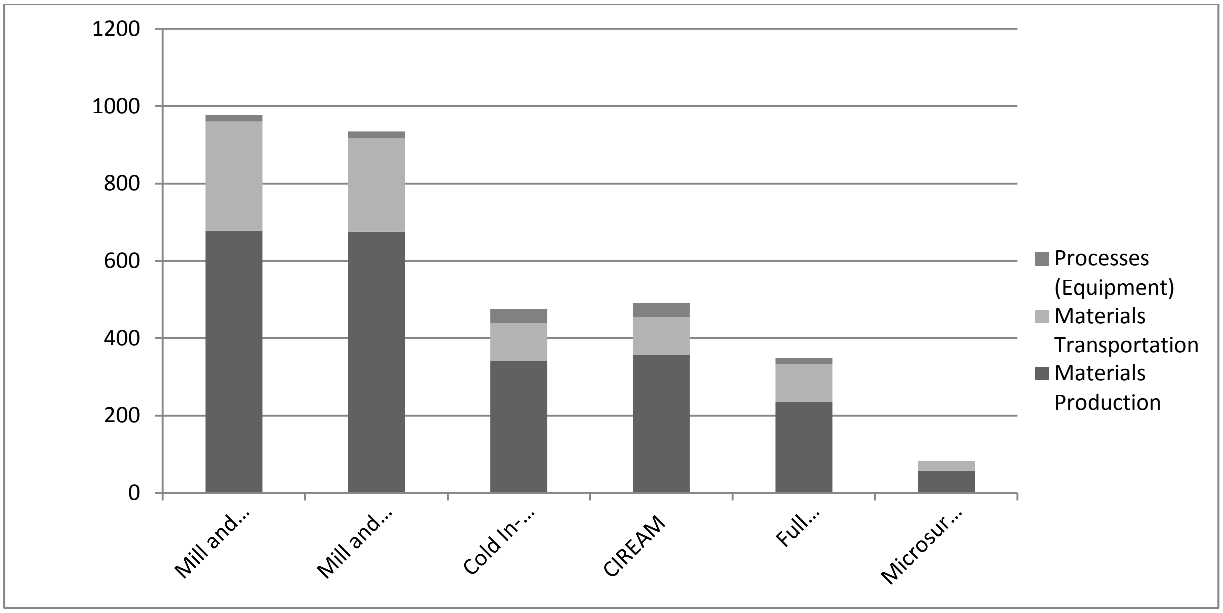


Figure D.49 – Rehabilitation Nitrous Oxide Emissions (Local)

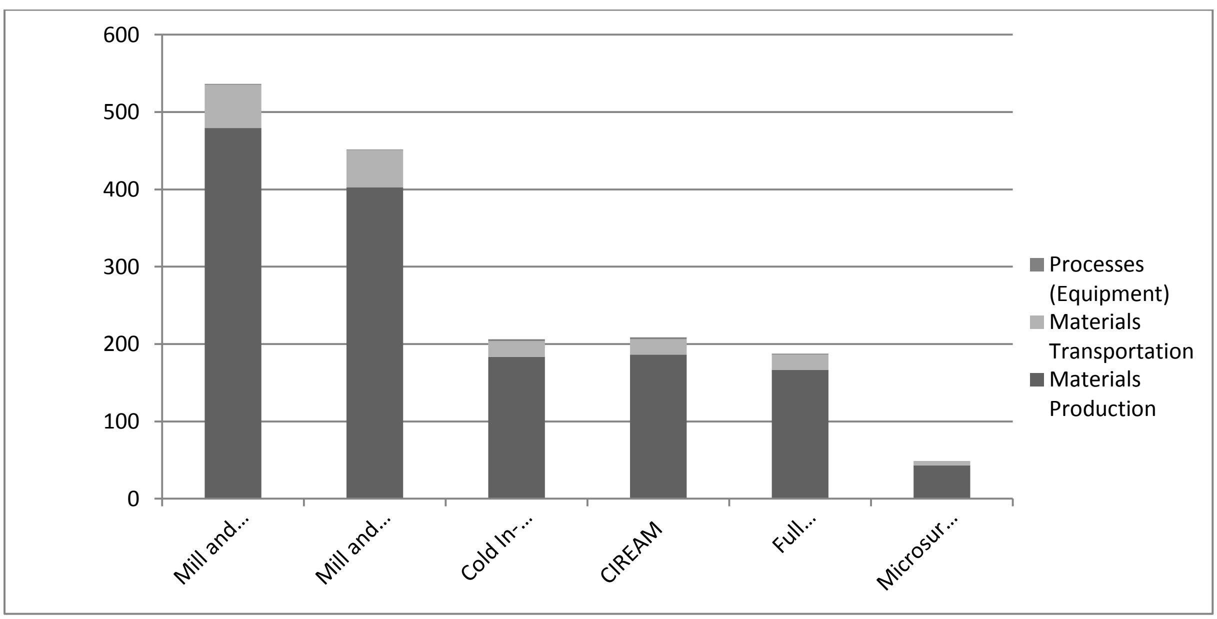


Figure D.50 – Rehabilitation Particulate Matter 10 Emissions (Local)

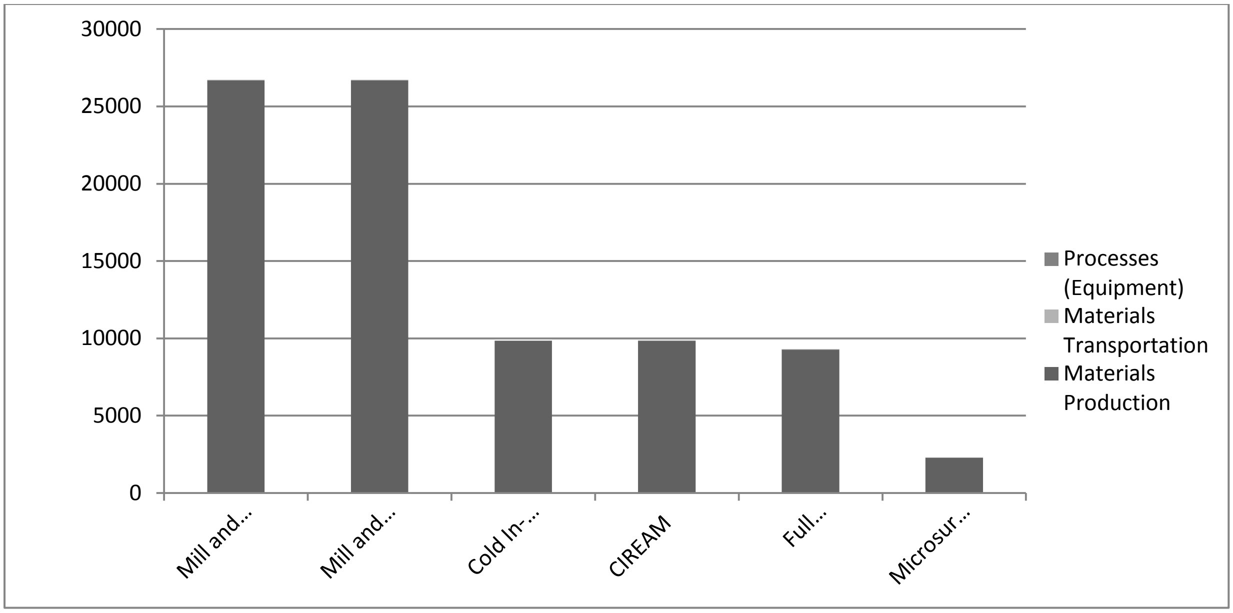


Figure D.51 – Rehabilitation Sulphur Dioxide Emissions (Local)

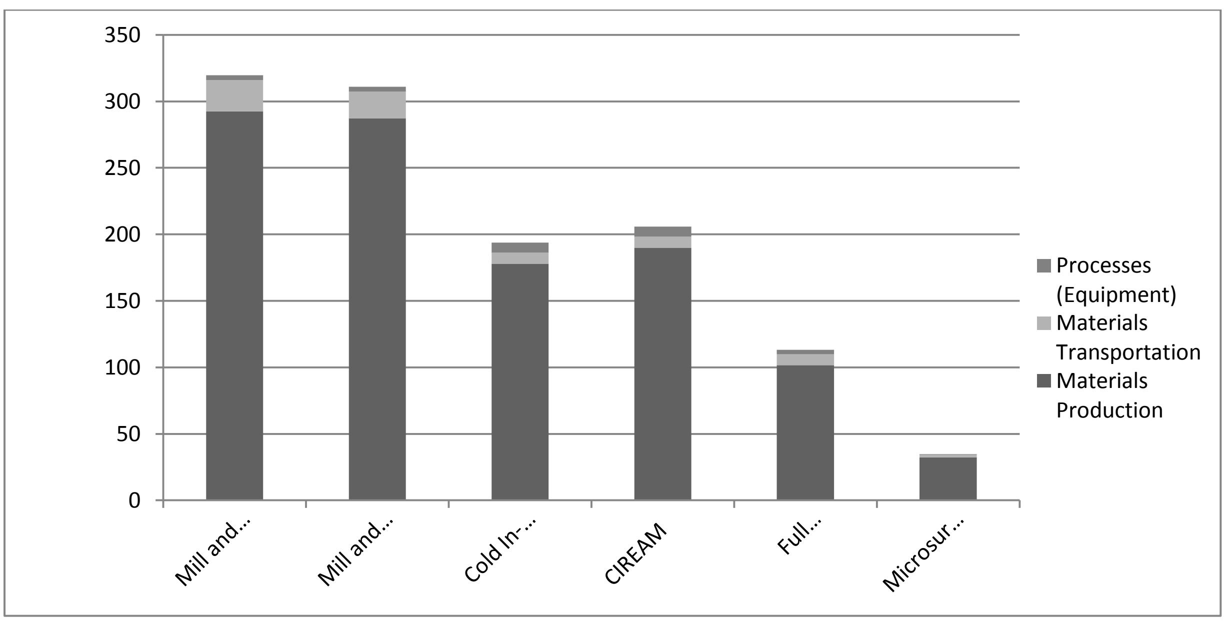


Figure D.52 – Rehabilitation Carbon Monoxide Emissions (Local)

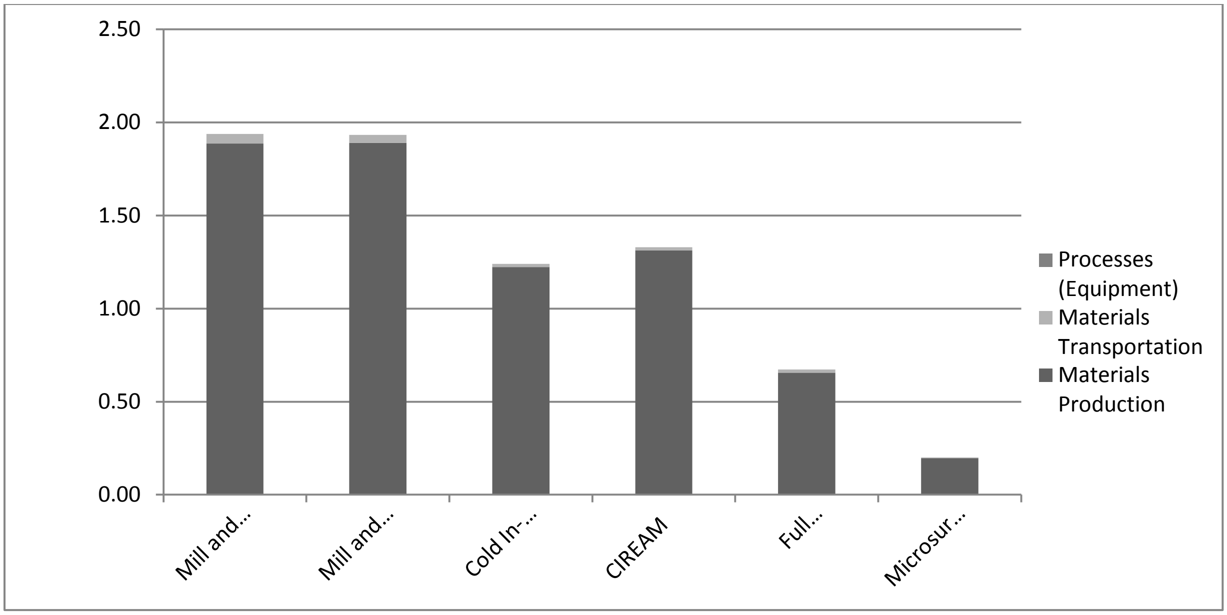


Figure D.53 – Rehabilitation Mercury Emissions (Local)

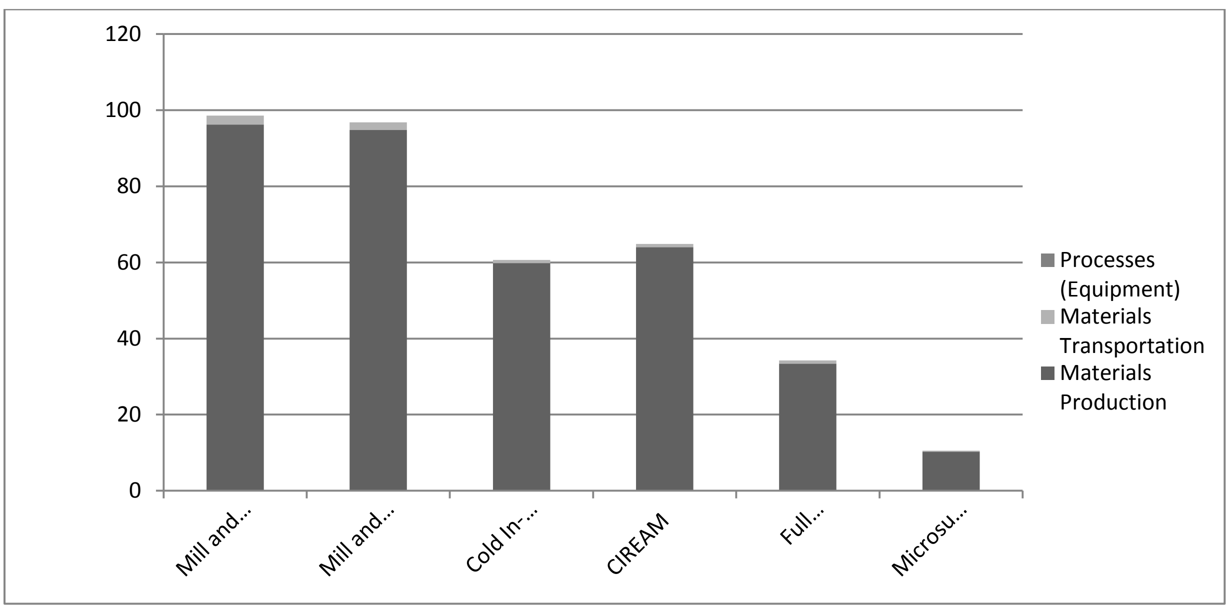


Figure D.54 – Rehabilitation Lead Emissions (Local)

OUTPUT – Graphical (Major Collector)

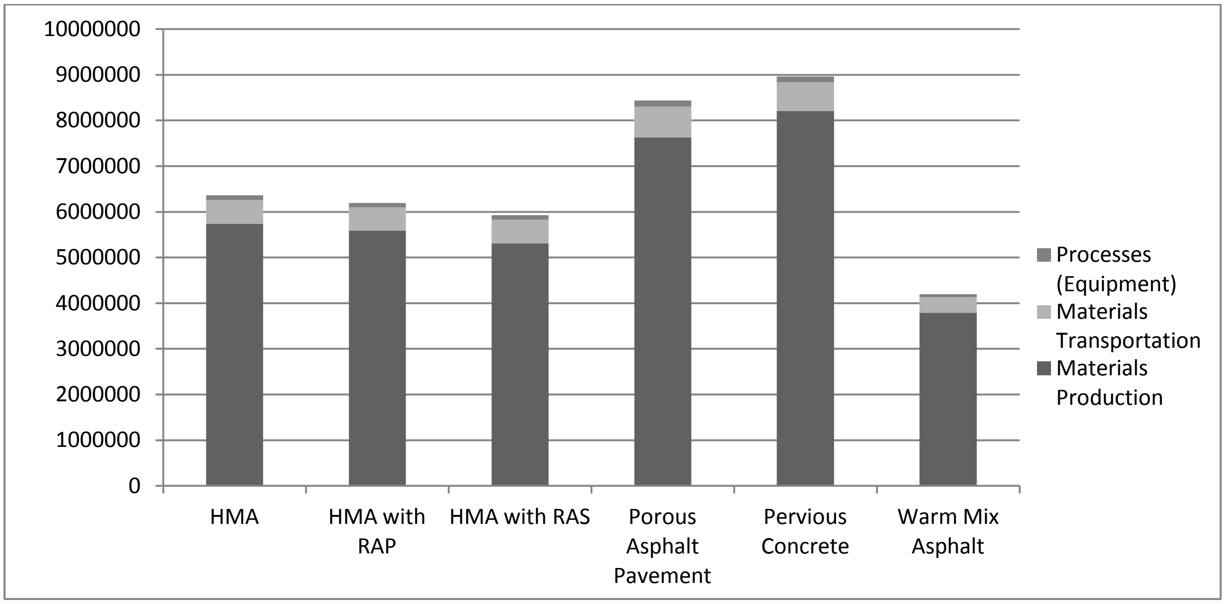


Figure D.55 – Initial Construction Energy Consumption (Major Collector)

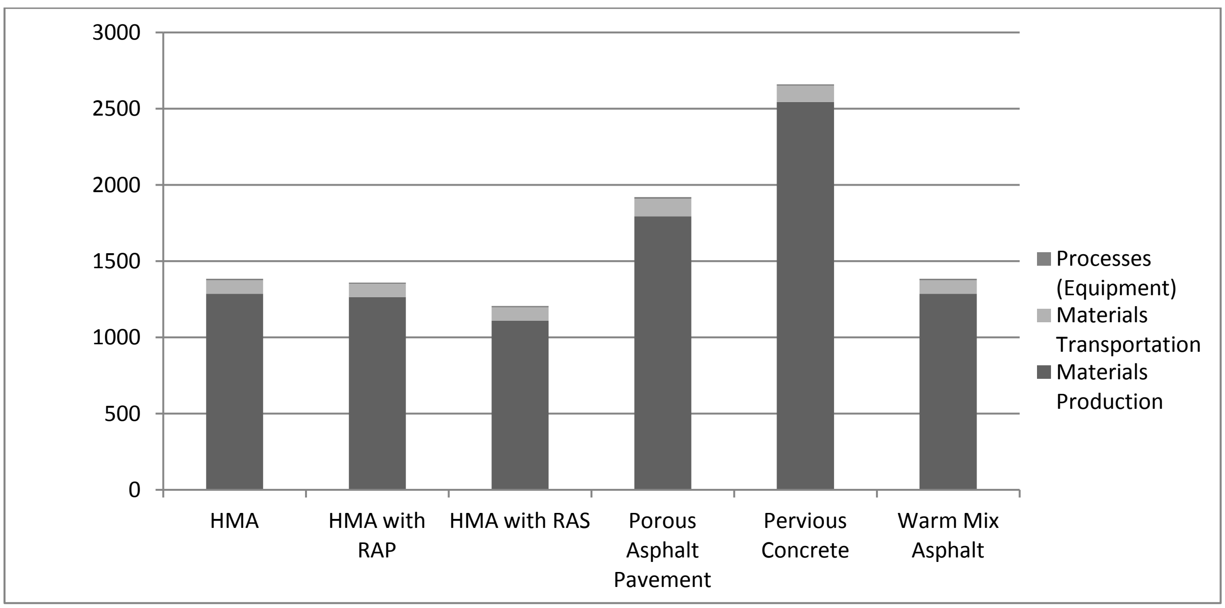


Figure D.56 – Initial Construction Water Consumption (Major Collector)

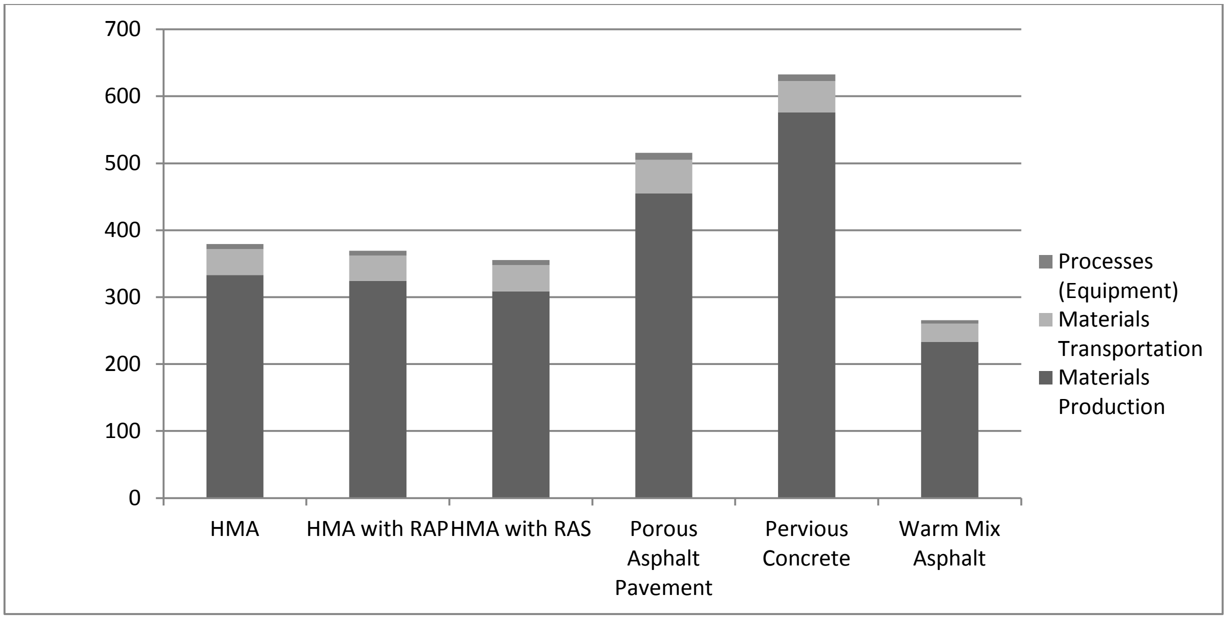


Figure D.57 – Initial Construction Carbon Dioxide Emissions (Major Collector)

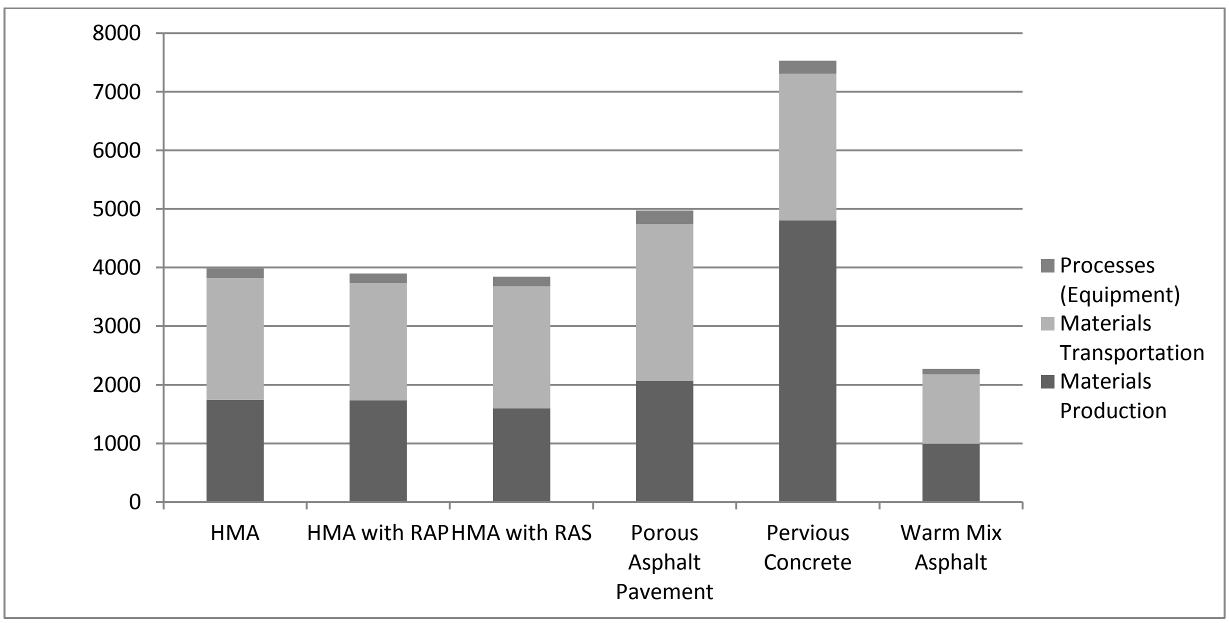


Figure D.58 – Initial Construction Nitrous Oxide Emissions (Major Collector)

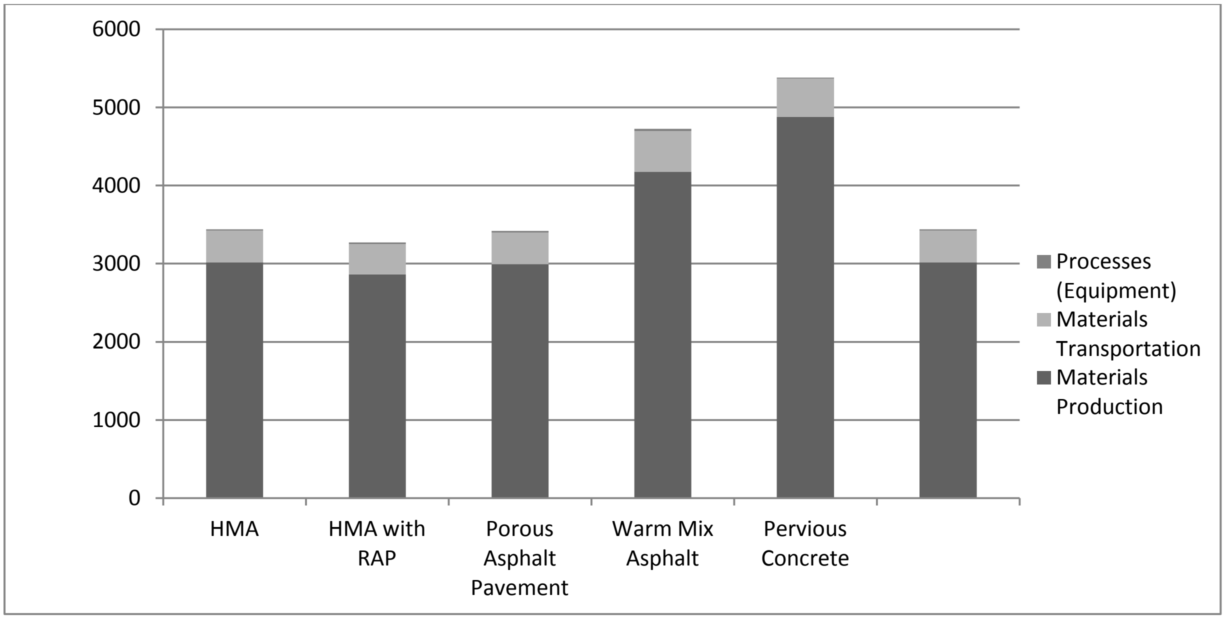


Figure D.59 – Initial Construction Particulate Matter 10 Emissions (Major Collector)

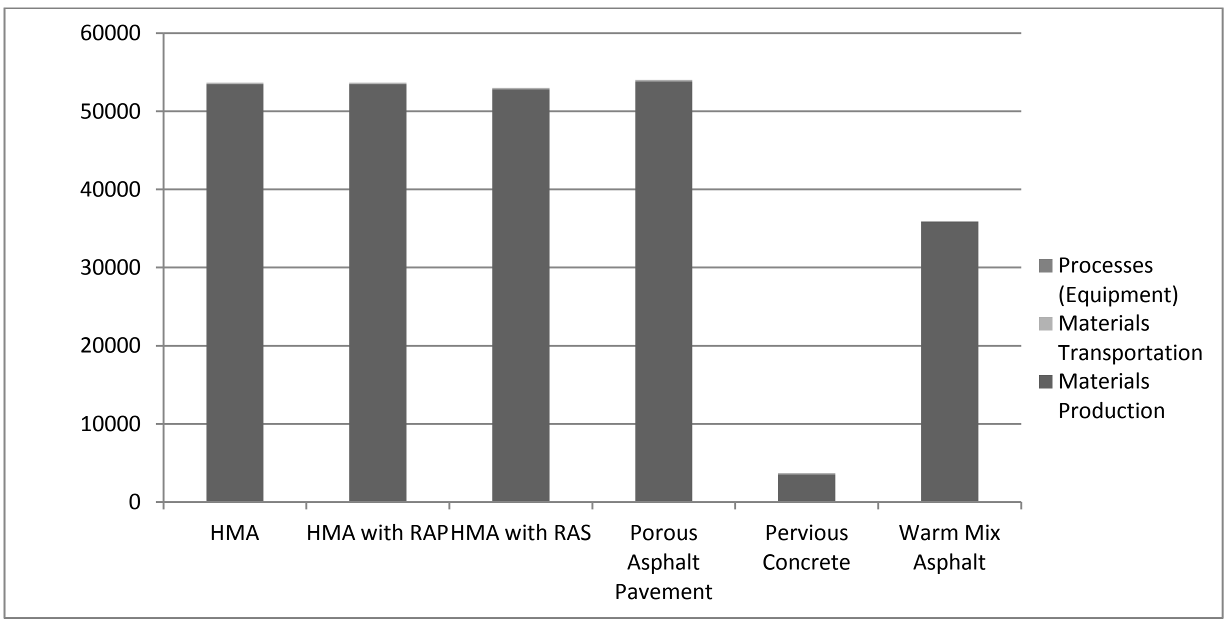


Figure D.60 – Initial Construction Sulphur Dioxide Emissions (Major Collector)

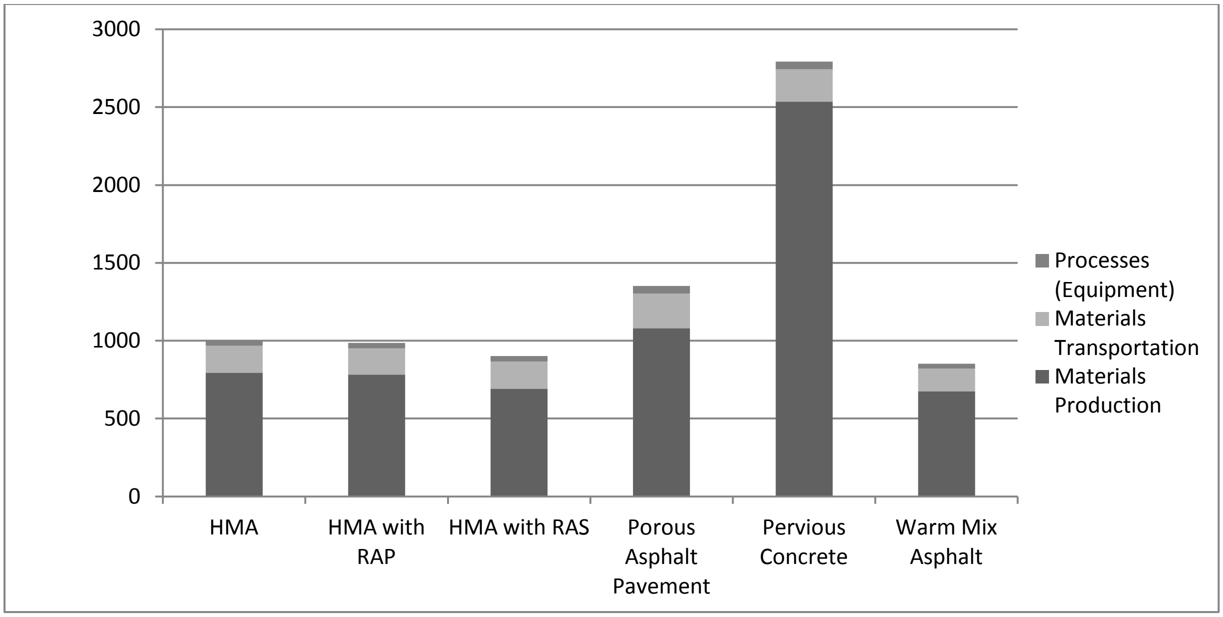


Figure D.61 – Initial Construction Carbon Monoxide Emissions (Major Collector)

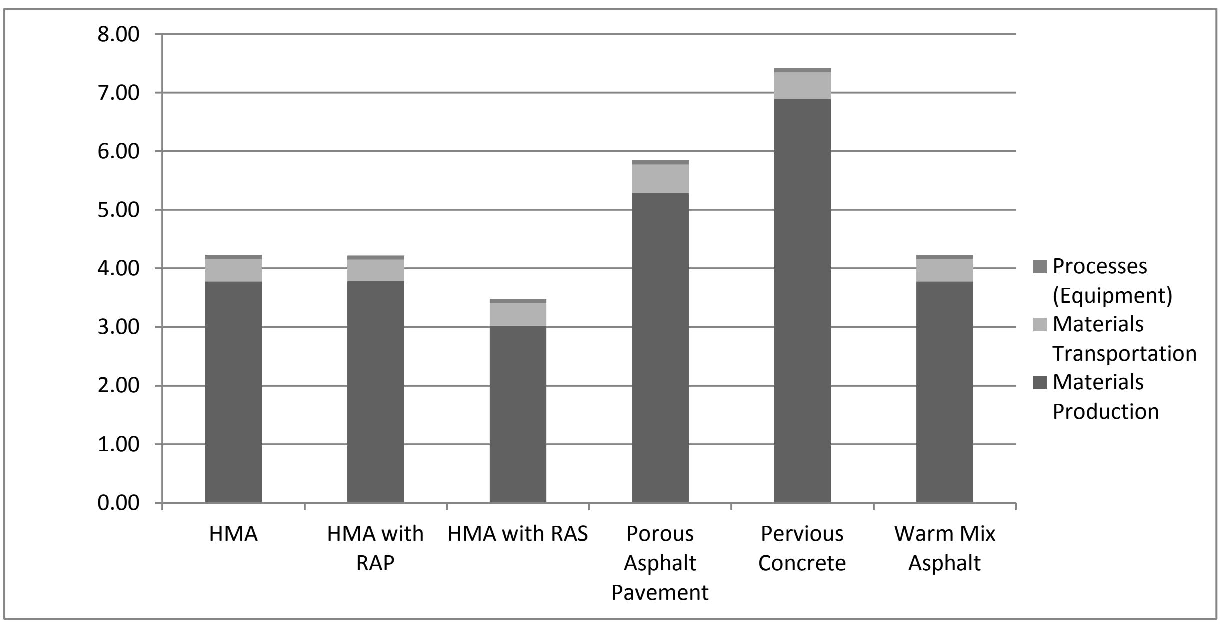


Figure D.62 – Initial Construction Mercury Emissions (Major Collector)

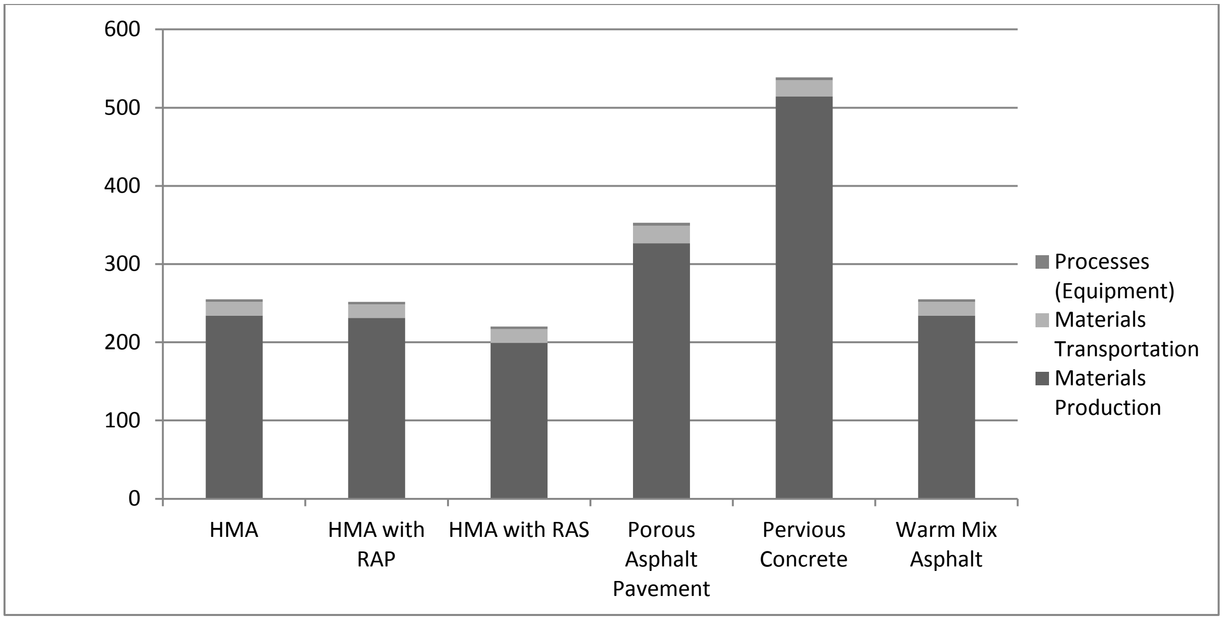


Figure D.63 – Initial Construction Lead Emissions (Major Collector)

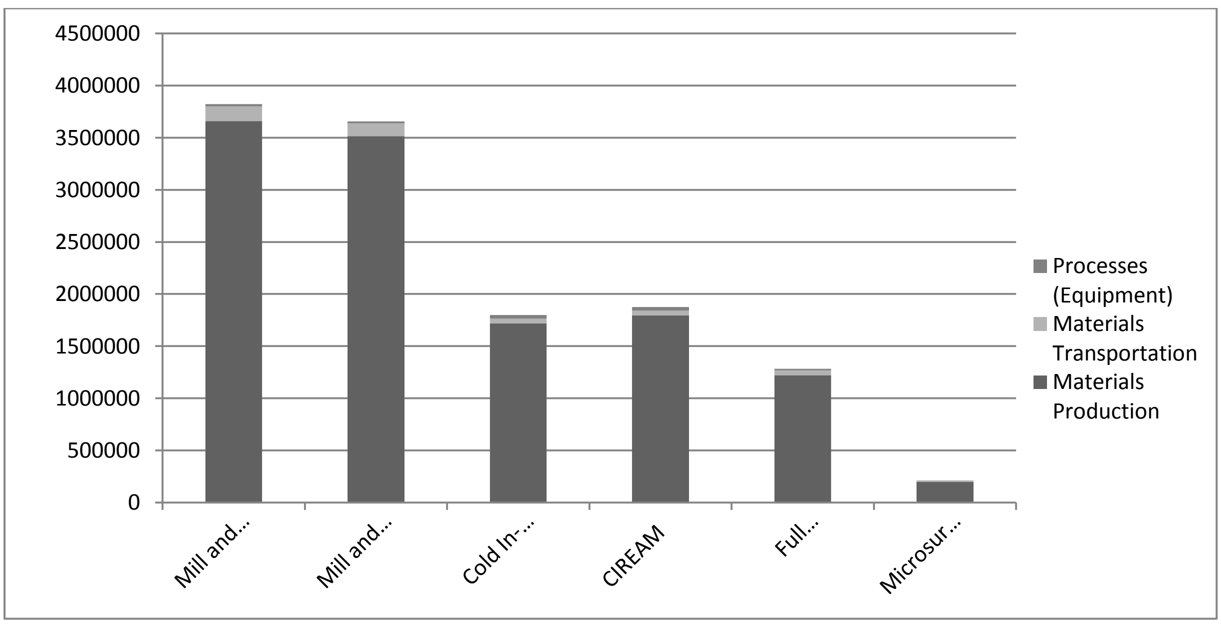


Figure D.64 – Rehabilitation Energy Consumption (Major Collector)

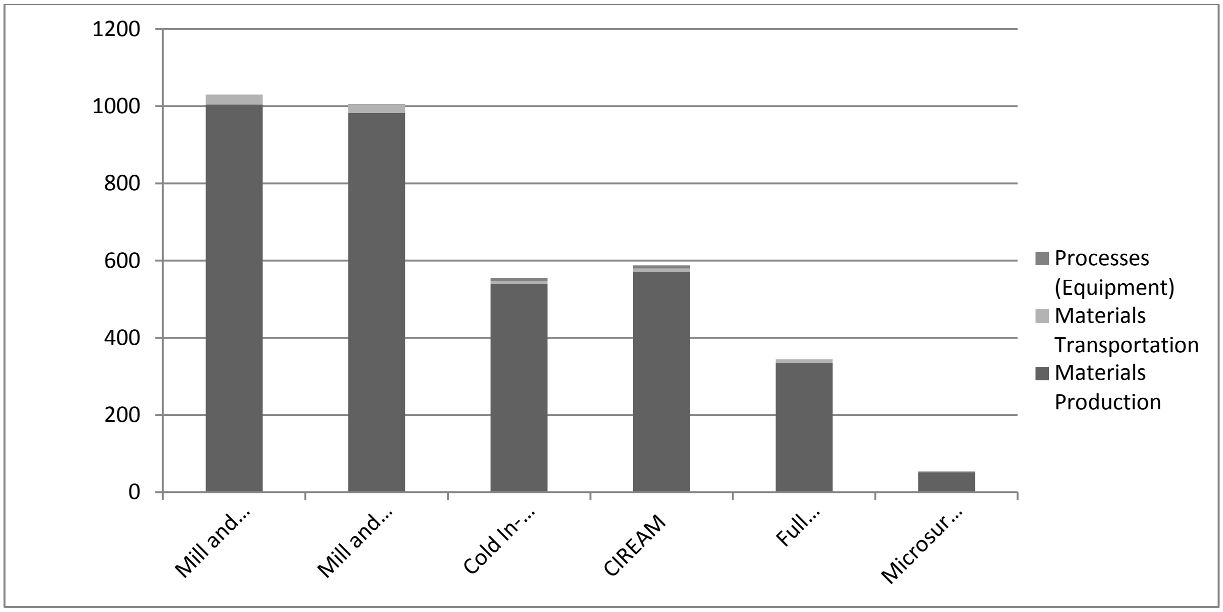


Figure D.65 – Rehabilitation Water Consumption (Major Collector)

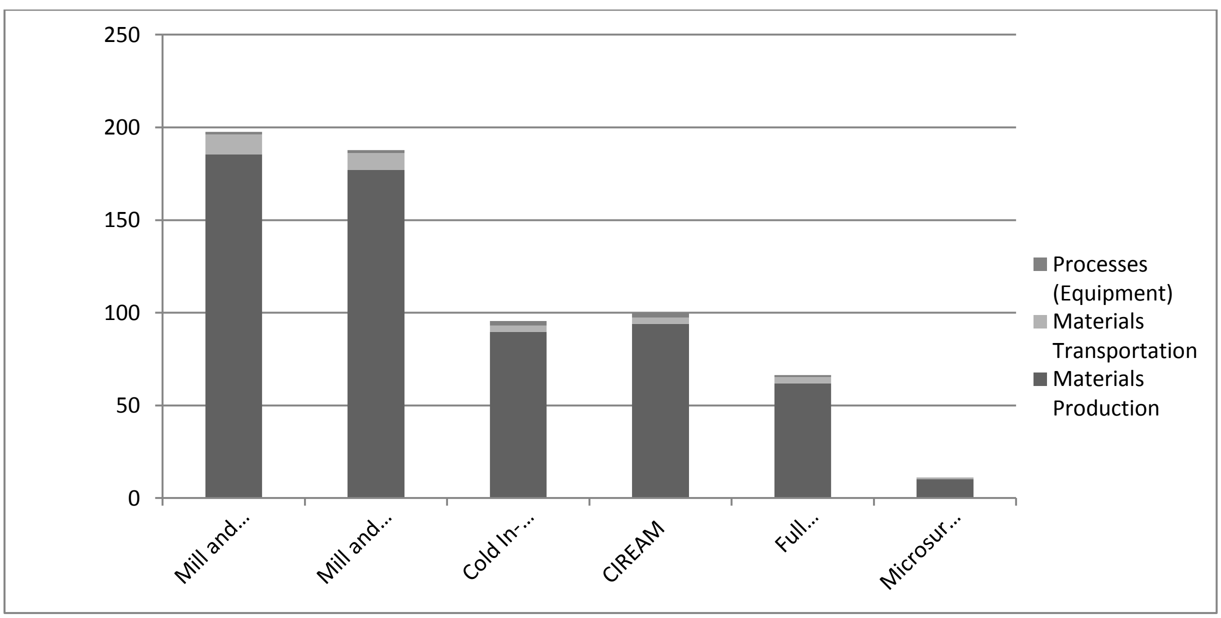


Figure D.66 – Rehabilitation Carbon Dioxide Emissions (Major Collector)

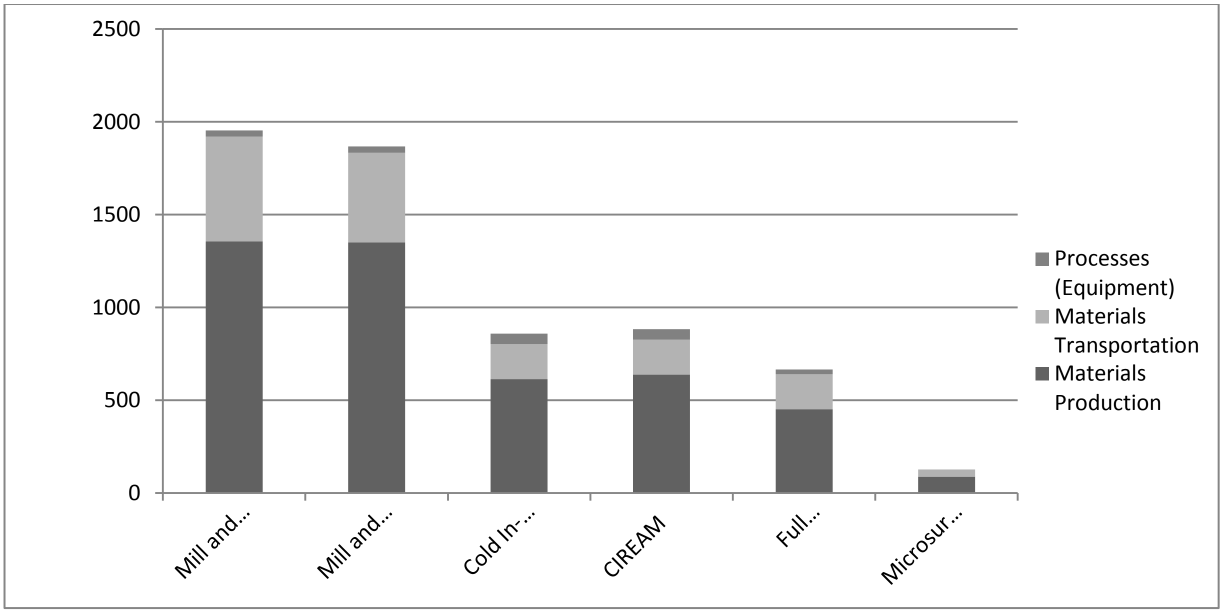


Figure D.67 – Rehabilitation Nitrous Oxide Emissions (Major Collector)

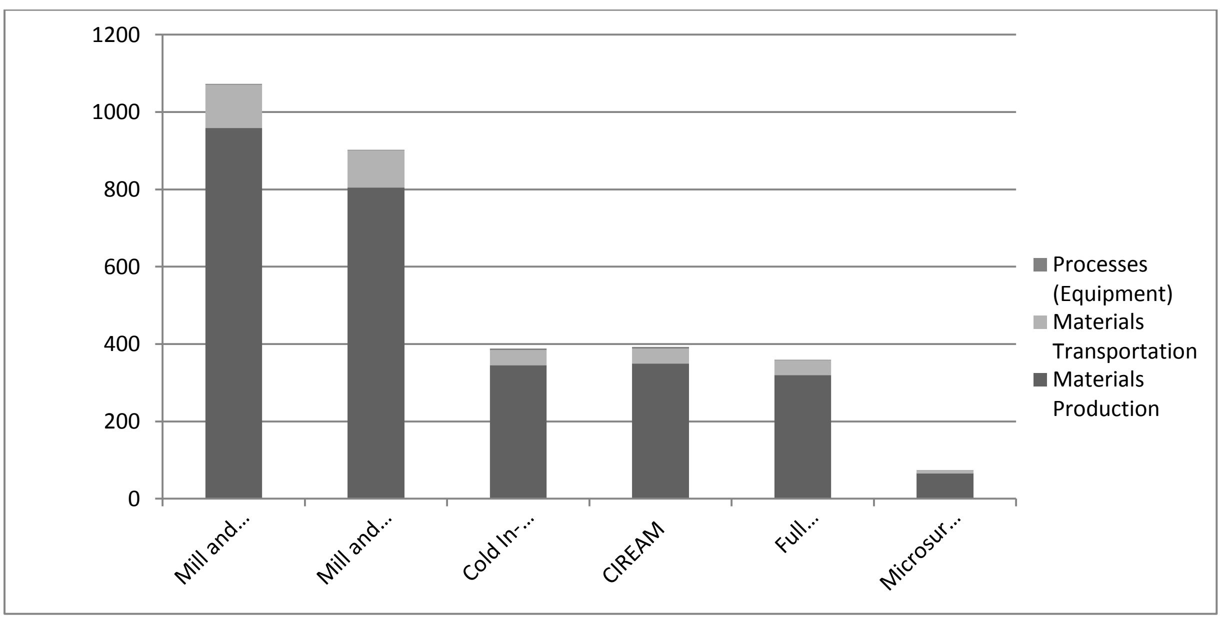


Figure D.68 – Rehabilitation Particulate Matter 10 Emissions (Major Collector)

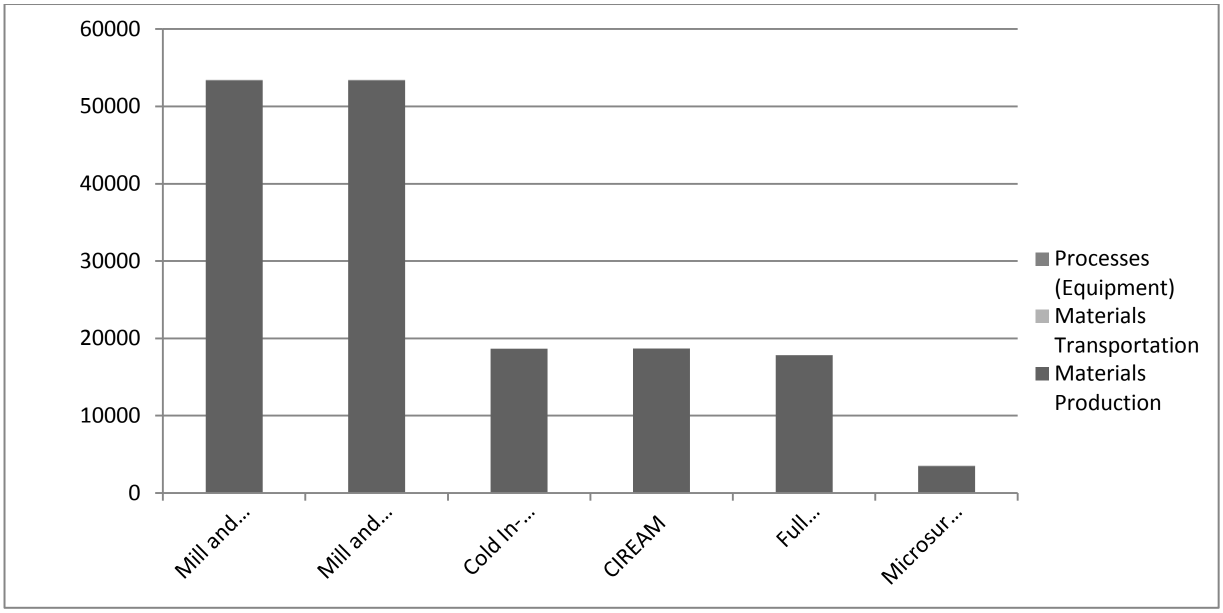


Figure D.69 – Rehabilitation Sulphur Dioxide Emissions (Major Collector)

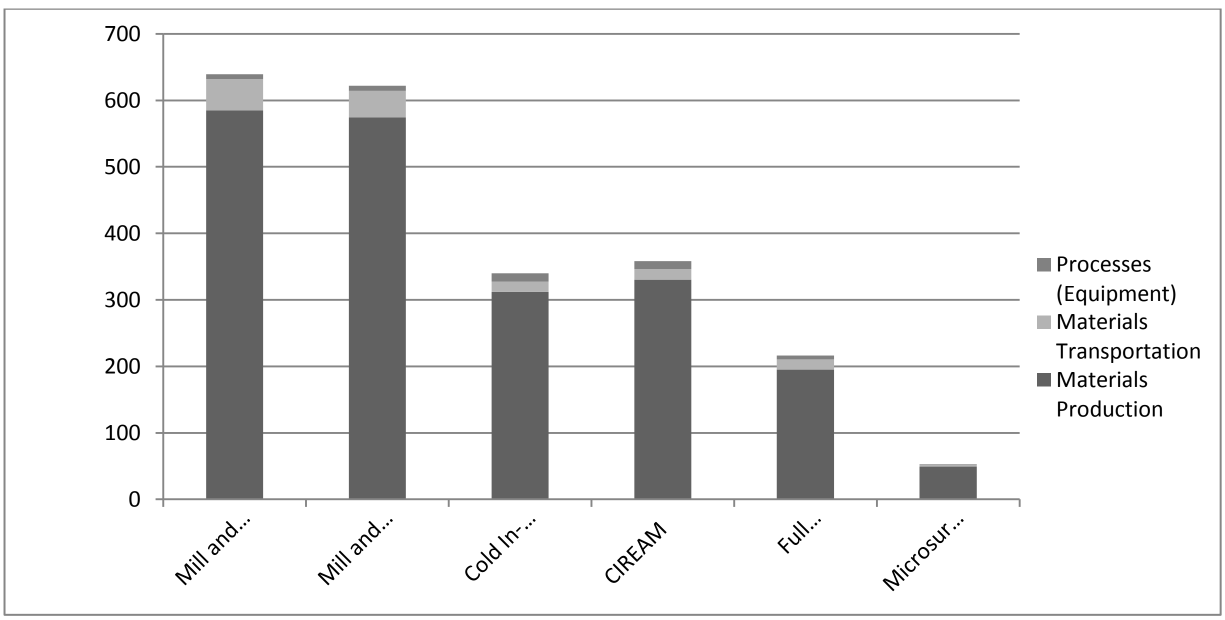


Figure D.70 – Rehabilitation Carbon Monoxide Emissions (Major Collector)

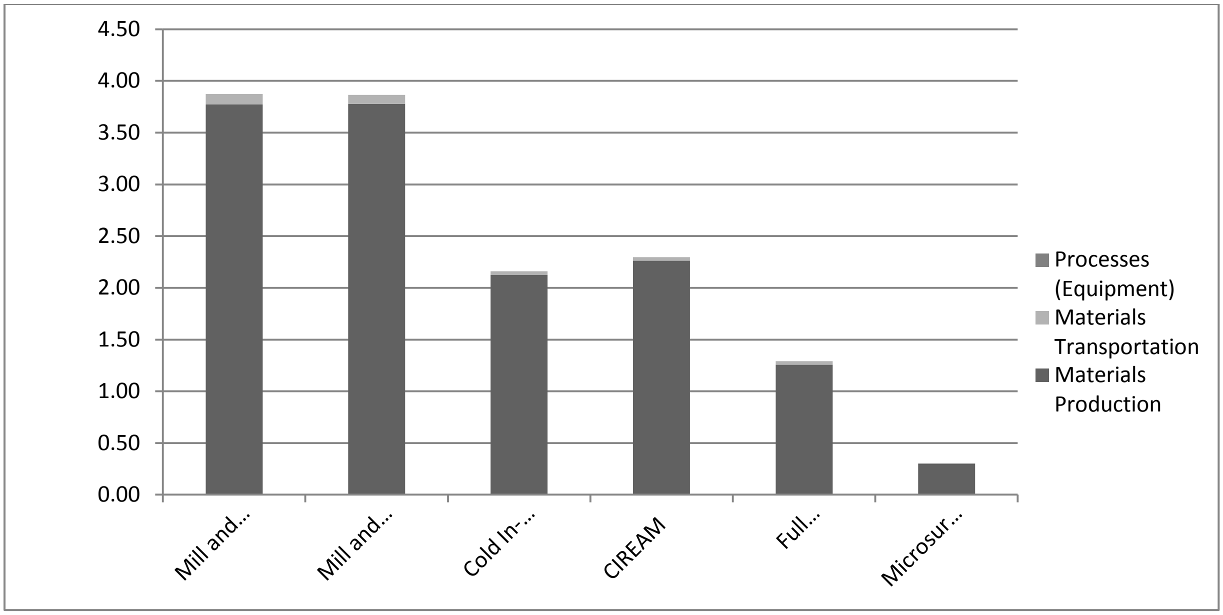


Figure D.71 – Rehabilitation Mercury Emissions (Major Collector)

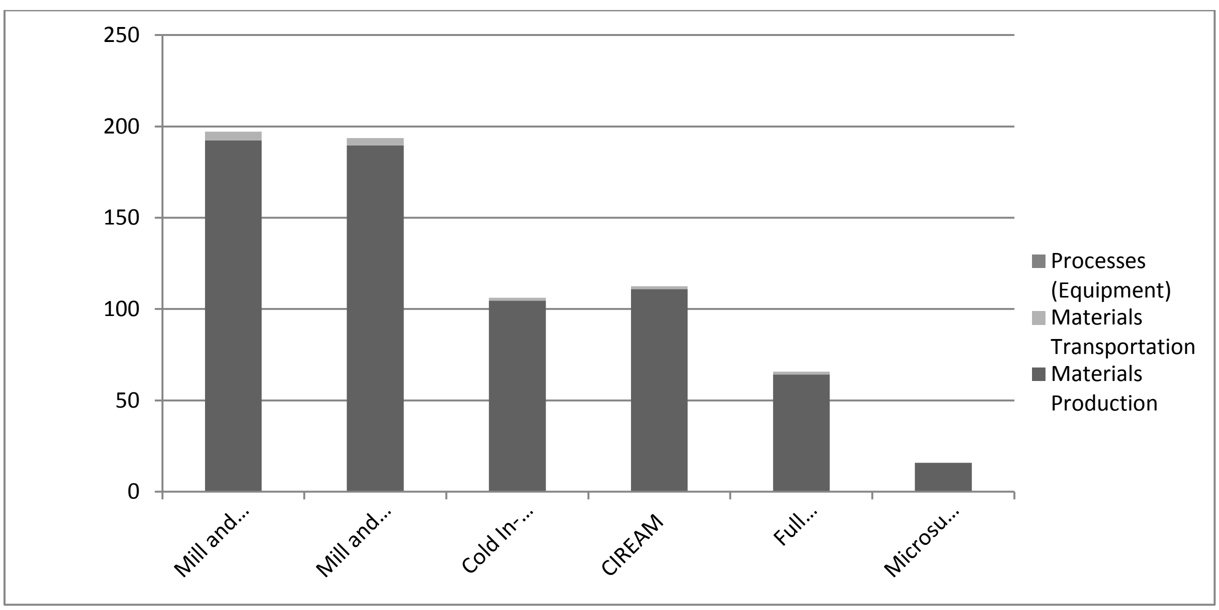


Figure D.72 – Rehabilitation Lead Emissions (Major Collector)

OUTPUT – Graphical (Minor Collector)

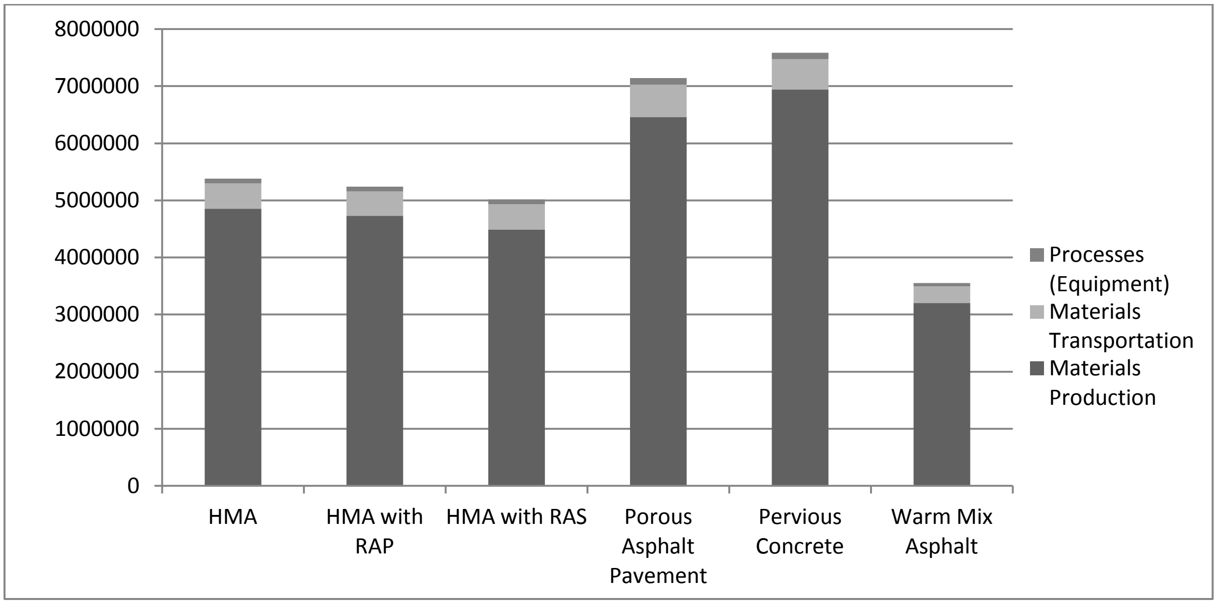


Figure D.73 – Initial Construction Energy Consumption (Minor Collector)

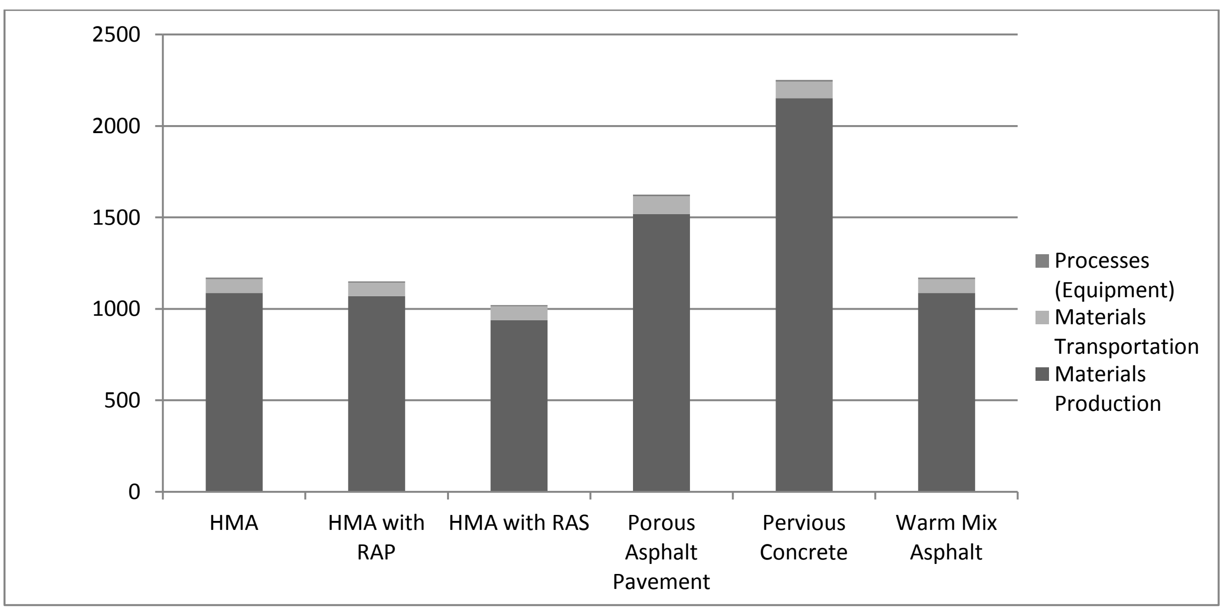


Figure D.74 – Initial Construction Water Consumption (Minor Collector)

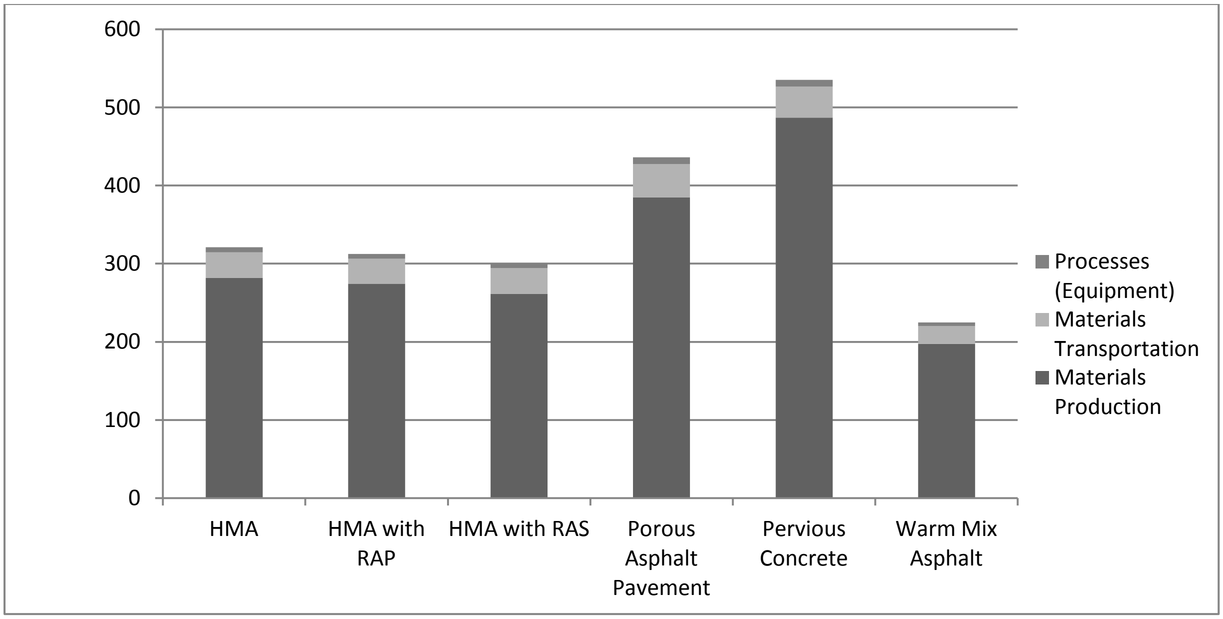


Figure D.75 – Initial Construction Carbon Dioxide Emissions (Minor Collector)

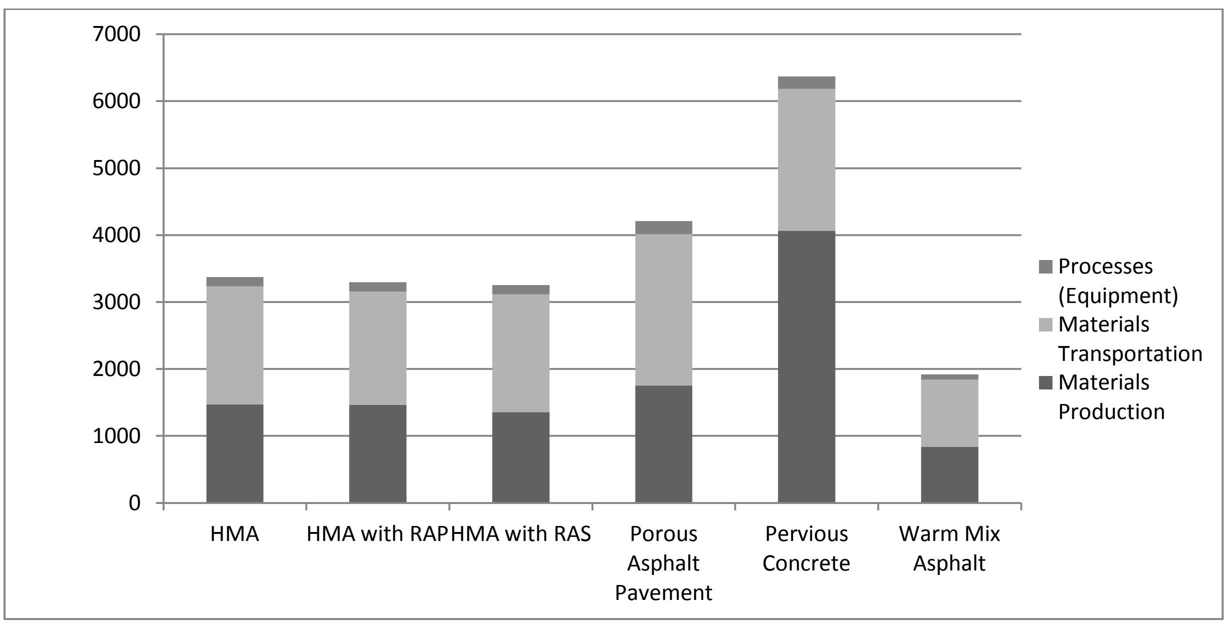


Figure D.76 – Initial Construction Nitrous Oxide Emissions (Minor Collector)

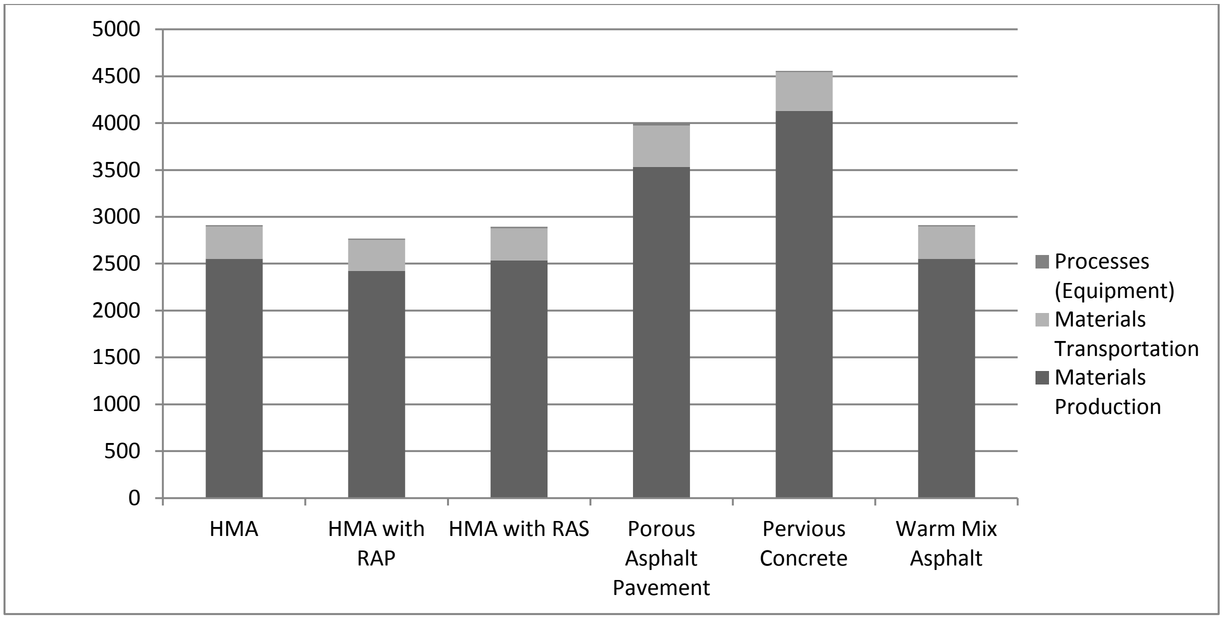


Figure D.77 – Initial Construction Particulate Matter 10 Emissions (Minor Collector)

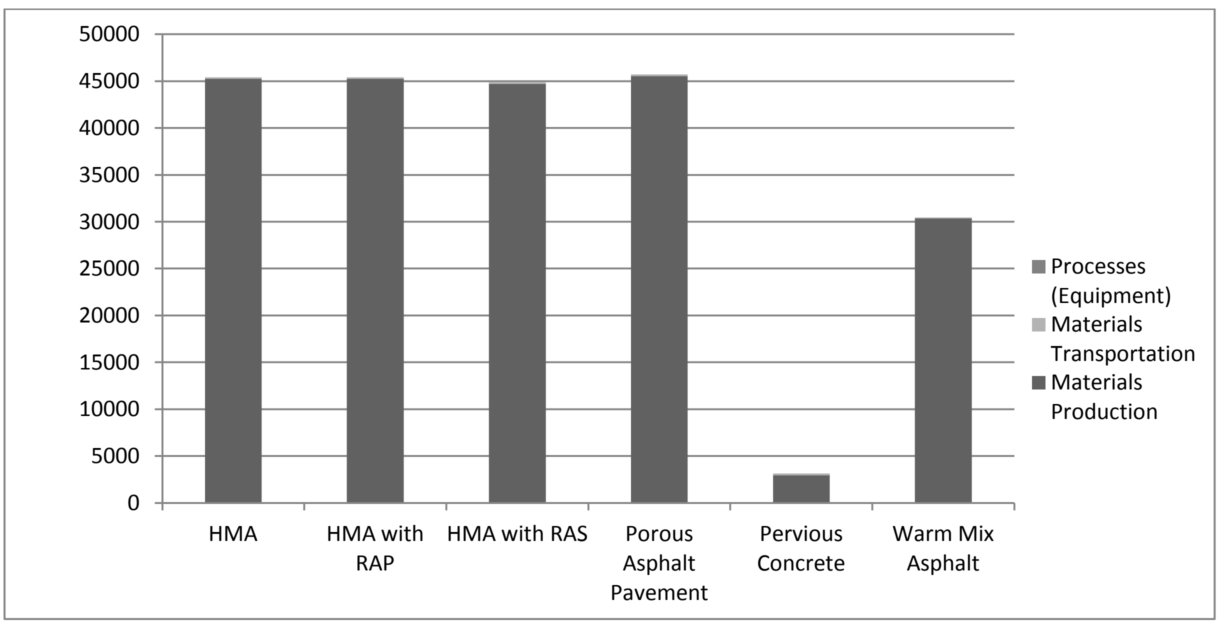


Figure D.78 – Initial Construction Sulphur Dioxide Emissions (Minor Collector)

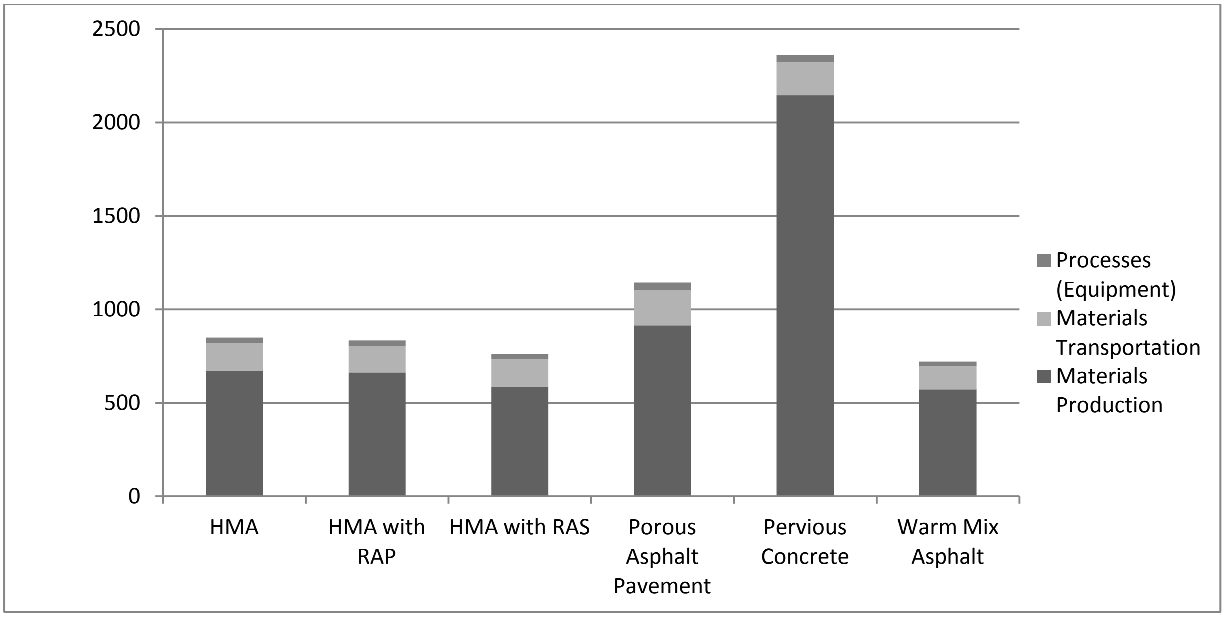


Figure D.79 – Initial Construction Carbon Monoxide Emissions (Minor Collector)

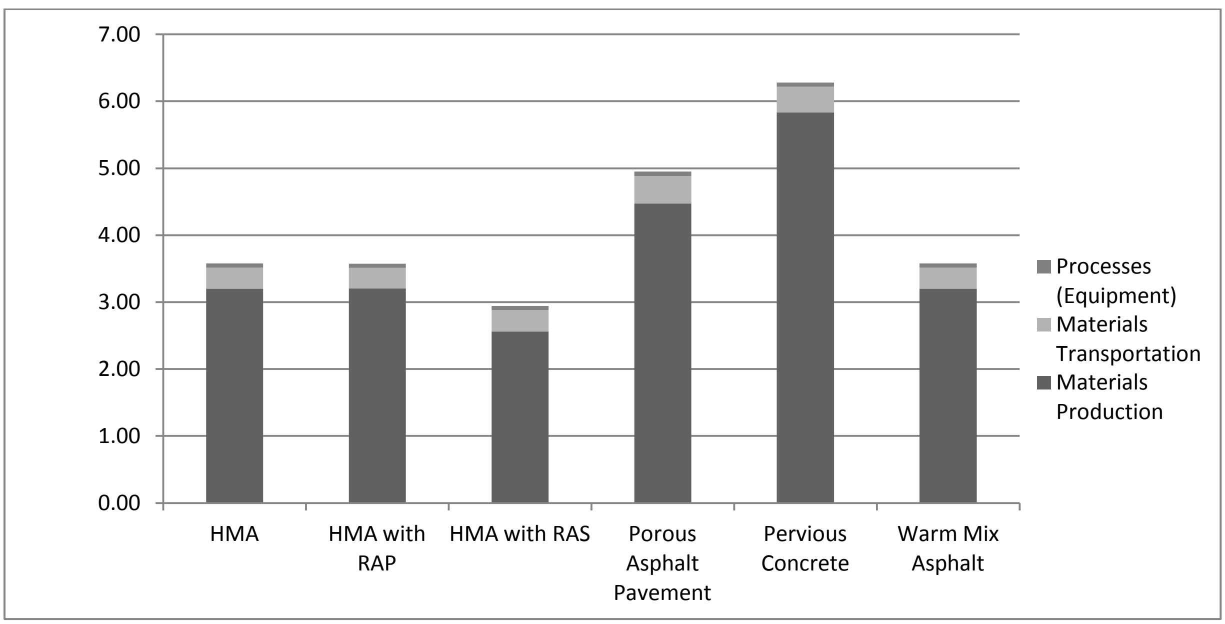


Figure D.80 – Initial Construction Mercury Emissions (Minor Collector)

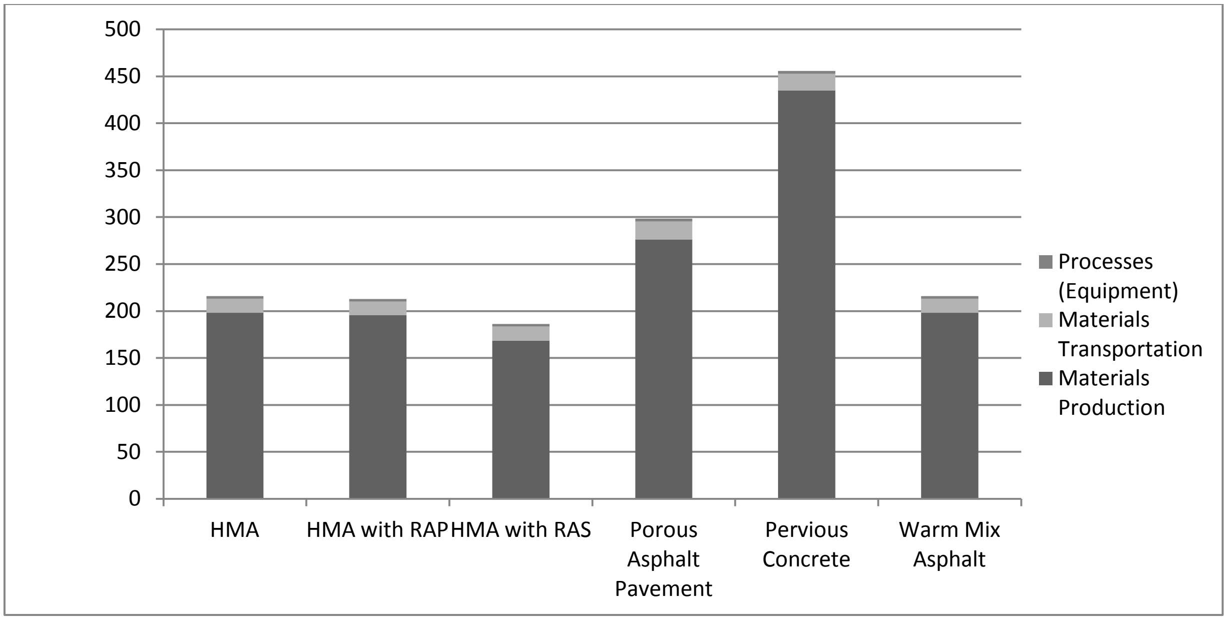


Figure D.81 – Initial Construction Lead Emissions (Minor Collector)

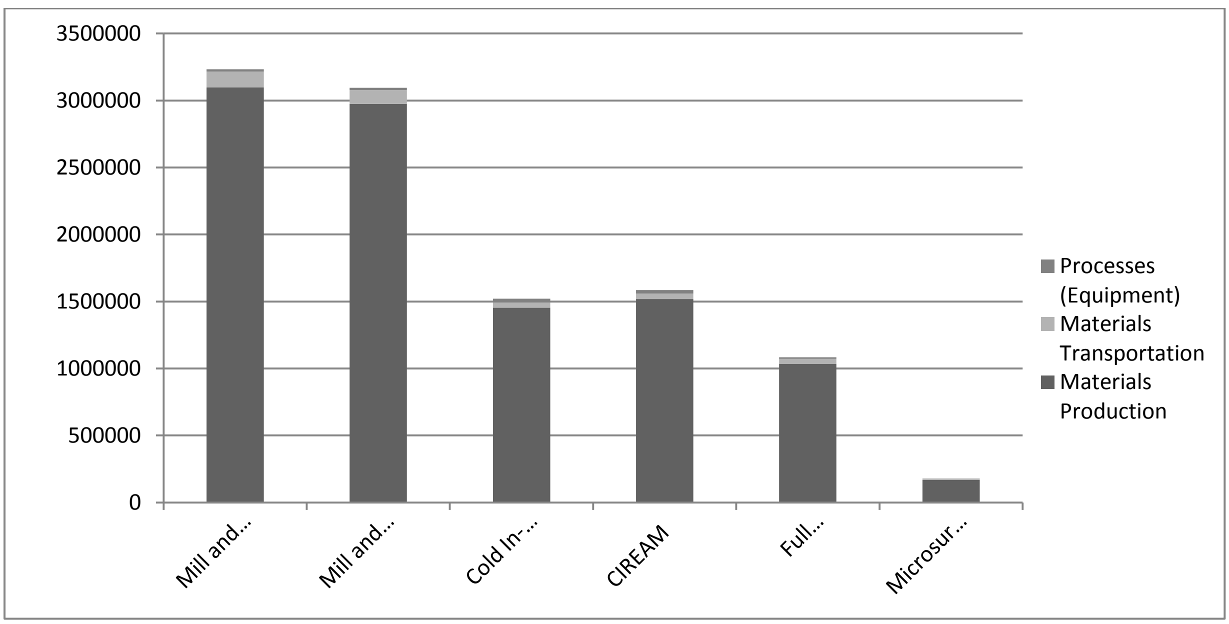


Figure D.82 – Rehabilitation Energy Consumption (Minor Collector)

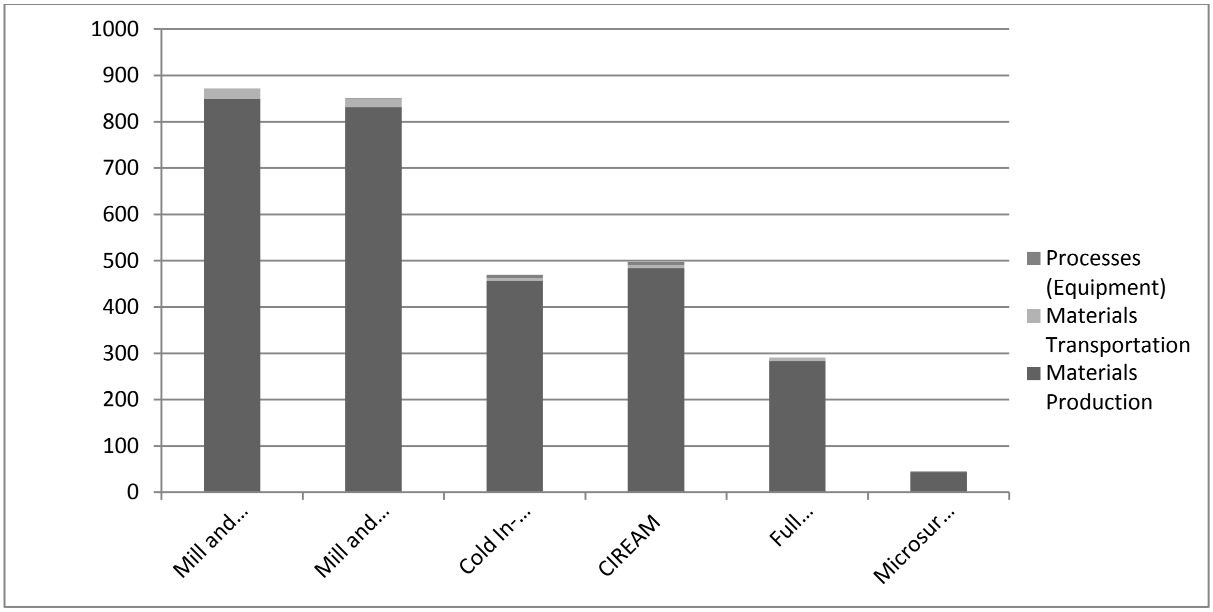


Figure D.83 – Rehabilitation Water Consumption (Minor Collector)

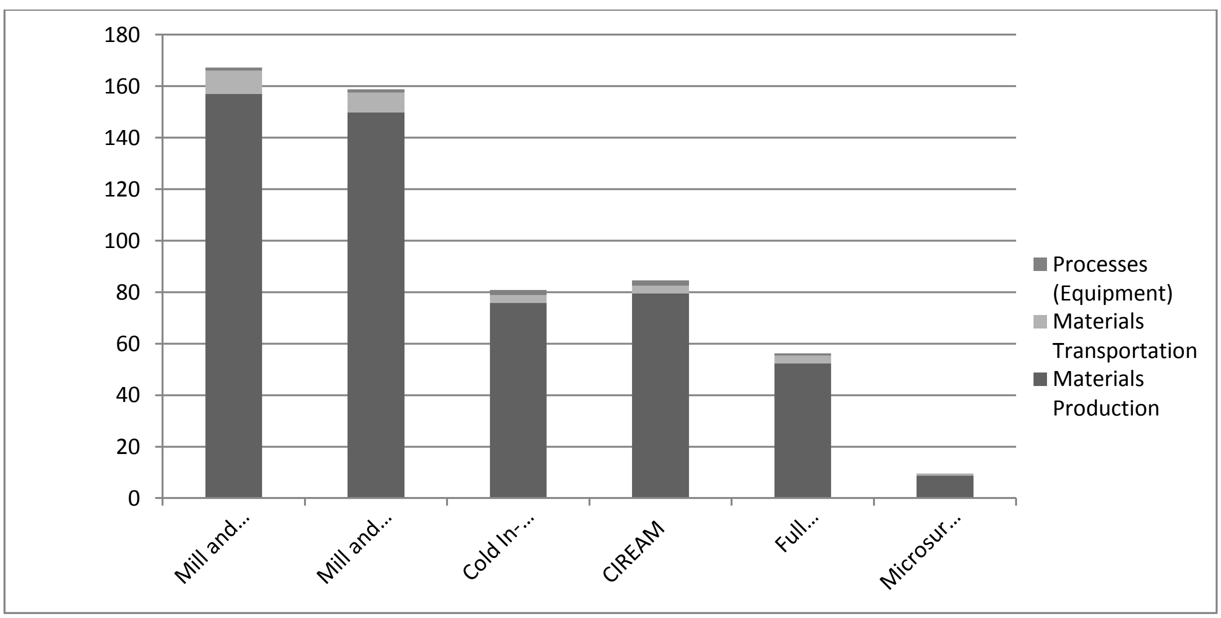


Figure D.84 – Rehabilitation Carbon Dioxide Emissions (Minor Collector)

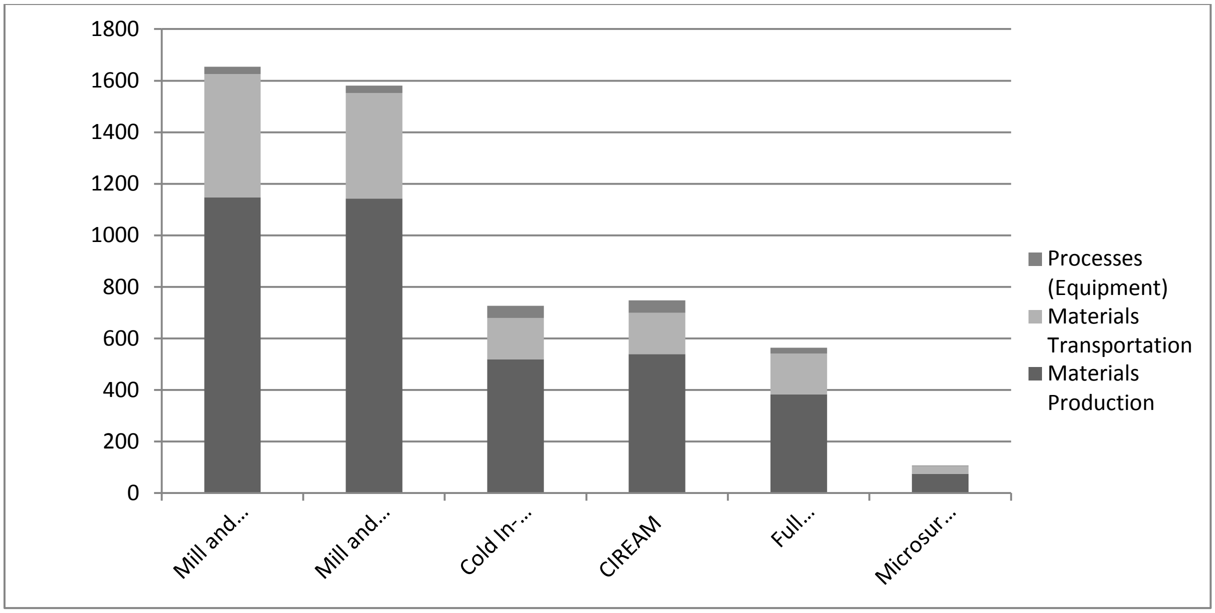


Figure D.85 – Rehabilitation Nitrous Oxide Emissions (Minor Collector)

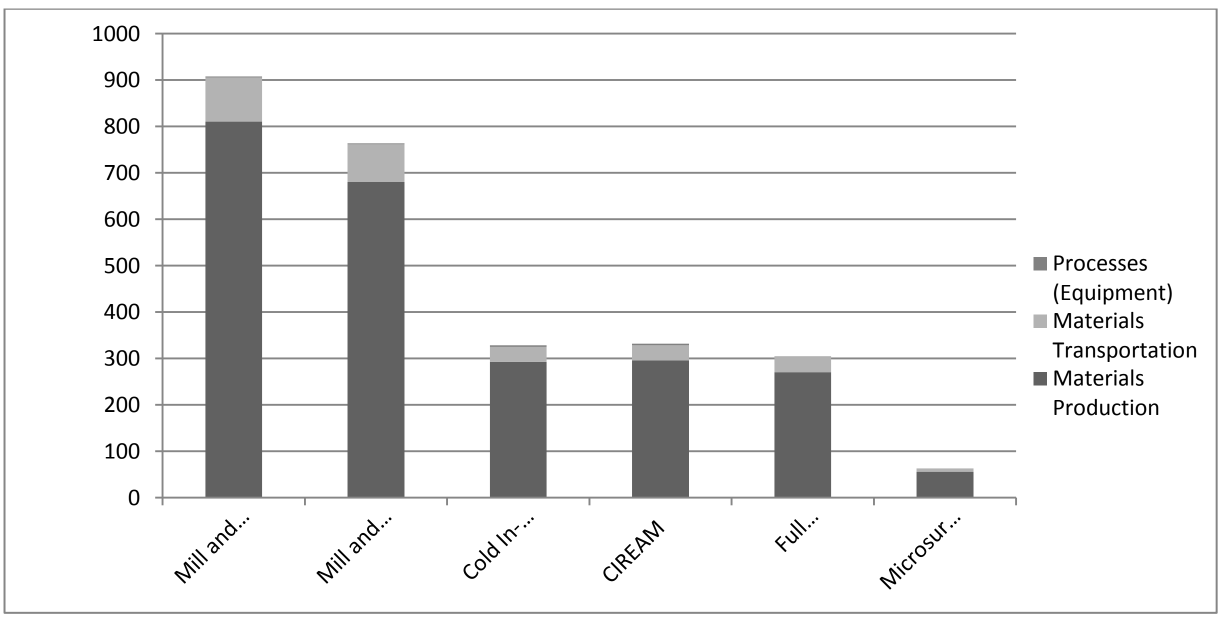


Figure D.86 – Rehabilitation Particulate Matter 10 Emissions (Minor Collector)

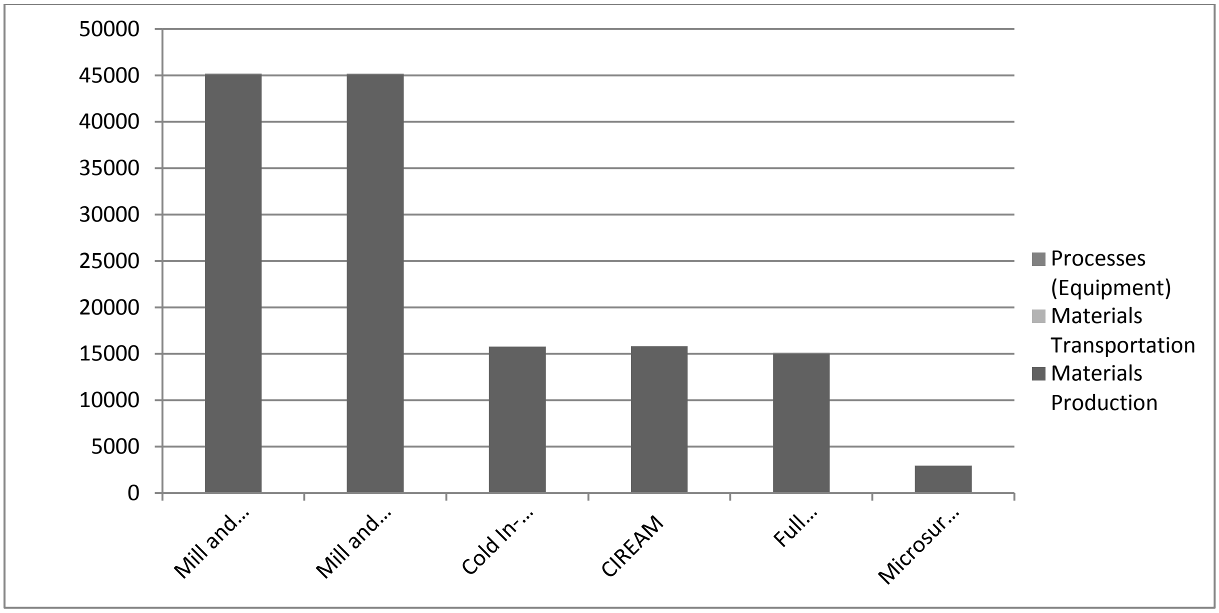


Figure D.87 – Rehabilitation Sulphur Dioxide Emissions (Minor Collector)

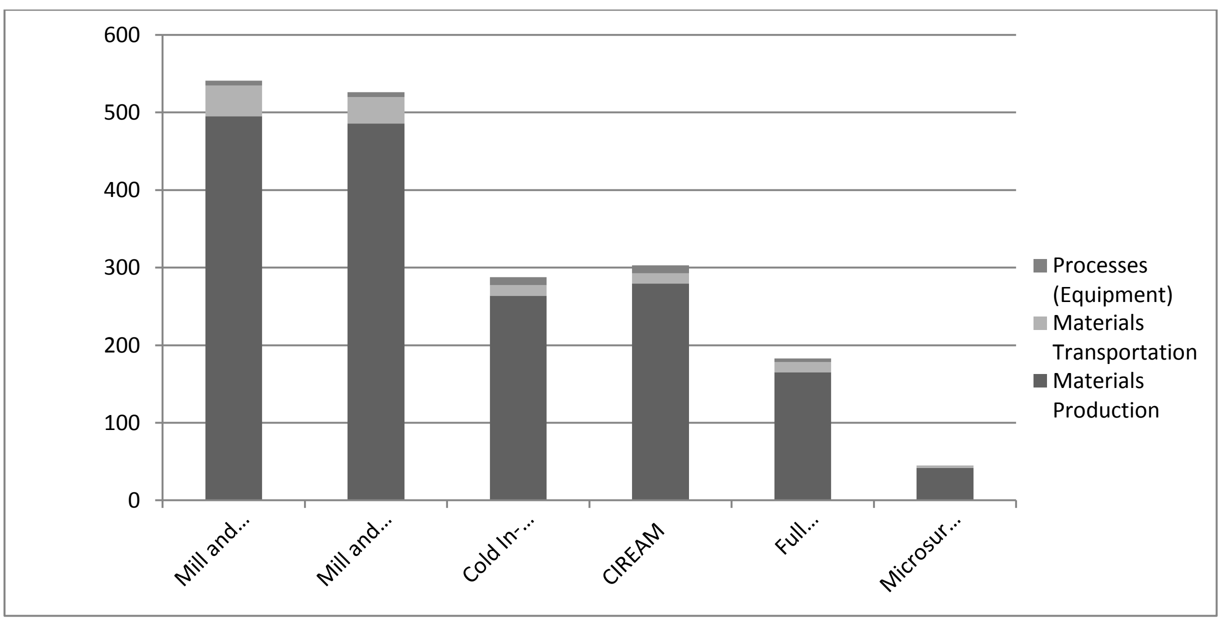


Figure D.88 – Rehabilitation Carbon Monoxide Emissions (Minor Collector)

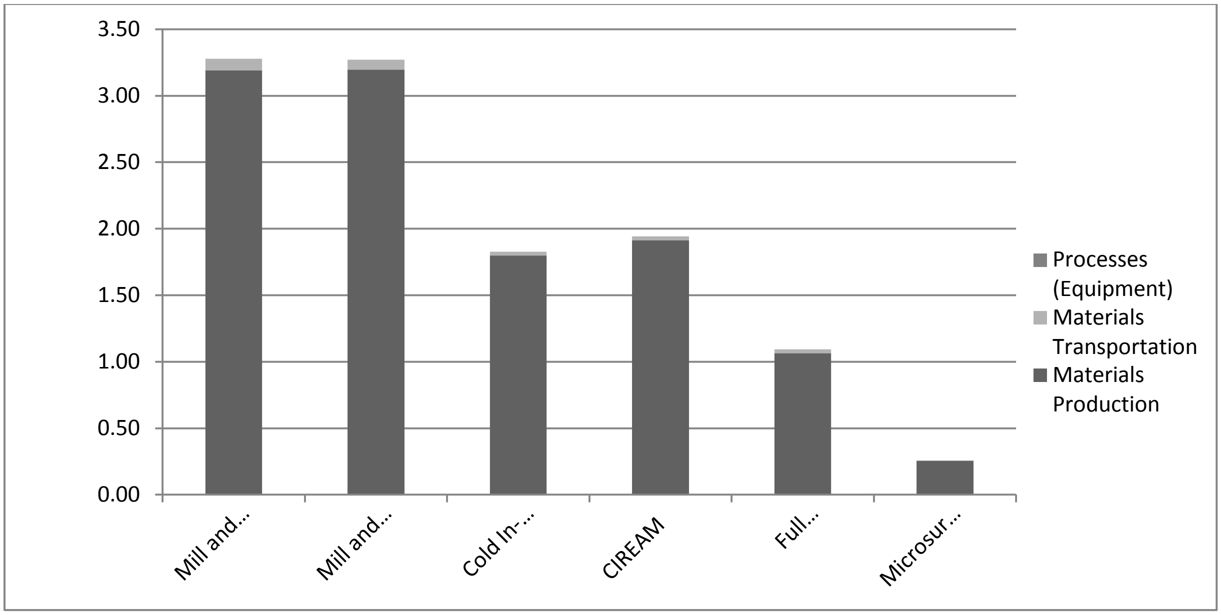


Figure D.89 – Rehabilitation Mercury Emissions (Minor Collector)

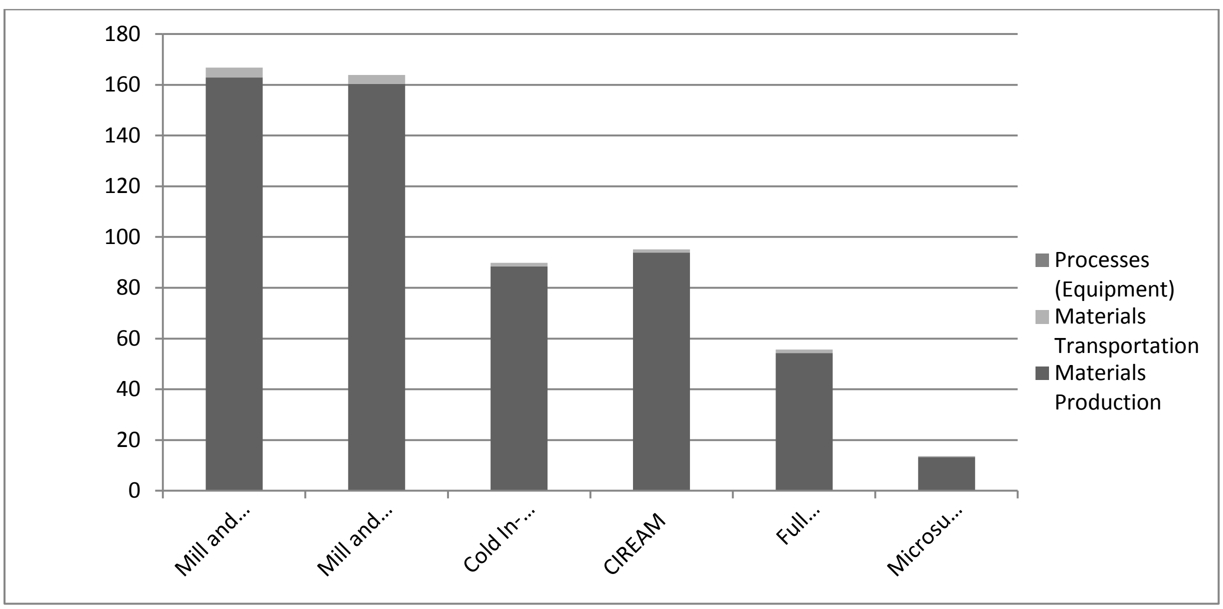


Figure D.90 – Rehabilitation Lead Emissions (Minor Collector)

Appendix D
Carbon Footprinting Data and Results

Table E.1 – Global Warming Potentials for all Greenhouse Gases [IPCC, 2007]

Industrial Designation or Common Name (years)	Chemical Formula	Lifetime (years)	Radiative Efficiency ($W\ m^{-2}\ ppb^{-1}$)	Global Warming Potential for Given Time Horizon			
				SAR‡ (100-yr)	20-yr	100-yr	500-yr
Carbon dioxide	CO_2	See below[a]	[b] $1.4x10^{-5}$	1	1	1	1
Methane[c]	CH_4	12[c]	$3.7x10^{-4}$	21	72	25	7.6
Nitrous oxide	N_2O	114	$3.03x10^{-3}$	310	289	298	153
Substances controlled by the Montreal Protocol							
CFC-11	CCl_3F	45	0.25	3,800	6,730	4,750	1,620
CFC-12	CCl_2F_2	100	0.32	8,100	11,000	10,900	5,200
CFC-13	$CClF_3$	640	0.25		10,800	14,400	16,400
CFC-113	CCl_2FCClF_2	85	0.3	4,800	6,540	6,130	2,700
CFC-114	$CClF_2CClF_2$	300	0.31		8,040	10,000	8,730
CFC-115	$CClF_2CF_3$	1,700	0.18		5,310	7,370	9,990
Halon-1301	$CBrF_3$	65	0.32	5,400	8,480	7,140	2,760
Halon-1211	$CBrClF_2$	16	0.3		4,750	1,890	575
Halon-2402	$CBrF_2CBrF_2$	20	0.33		3,680	1,640	503
Carbon tetrachloride	CCl_4	26	0.13	1,400	2,700	1,400	435
Methyl bromide	CH_3Br	0.7	0.01		17	5	1
Methyl chloroform	CH_3CCl_3	5	0.06		506	146	45
HCFC-22	$CHClF_2$	12	0.2	1,500	5,160	1,810	549
HCFC-123	$CHCl_2CF_3$	1.3	0.14	90	273	77	24
HCFC-124	$CHClFCF_3$	5.8	0.22	470	2,070	609	185
HCFC-141b	CH_3CCl_2F	9.3	0.14		2,250	725	220
HCFC-142b	CH_3CClF_2	17.9	0.2	1,800	5,490	2,310	705
HCFC-225ca	$CHCl_2CF_2CF_3$	1.9	0.2		429	122	37
HCFC-225cb	$CHClFCF_2CClF_2$	5.8	0.32		2,030	595	181
Hydrofluorocarbons							
HFC-23	CHF_3	270	0.19	11,700	12,000	14,800	12,200
HFC-32	CH_2F_2	4.9	0.11	650	2,330	675	205
HFC-125	CHF_2CF_3	29	0.23	2,800	6,350	3,500	1,100
HFC-134a	CH_2FCF_3	14	0.16	1,300	3,830	1,430	435
HFC-143a	CH_3CF_3	52	0.13	3,800	5,890	4,470	1,590
HFC-152a	CH_3CHF_2	1.4	0.09	140	437	124	38
HFC-227ea	CF_3CHFCF_3	34.2	0.26	2,900	5,310	3,220	1,040
HFC-236fa	$CF_3CH_2CF_3$	240	0.28	6,300	8,100	9,810	7,660
HFC-245fa	$CHF_2CH_2CF_3$	7.6	0.28		3,380	1030	314
HFC-365mfc	$CH_3CF_2CH_2CF_3$	8.6	0.21		2,520	794	241
HFC-43-10mee	$CF_3CHFCHFCF_2CF_3$	15.9	0.4	1,300	4,140	1,640	500
Perfluorinated compounds							
Sulphur hexafluoride	SF_6	3,200	0.52	23,900	16,300	22,800	32,600
Nitrogen trifluoride	NF_3	740	0.21		12,300	17,200	20,700
PFC-14	CF_4	50,000	0.10	6,500	5,210	7,390	11,200
PFC-116	C_2F_6	10,000	0.26	9,200	8,630	12,200	18,200

Industrial Designation or Common Name (years)	Chemical Formula	Lifetime (years)	RadiativeEfficiency (W m–2 ppb–1)	Global Warming Potential for Given Time Horizon SAR‡ (100-yr)	20-yr	100-yr	500-yr
Perfluorinated compounds (continued)							
PFC-218		2,600	0.26	7,000	6,310	8,830	12,500
PFC-318		3,200	0.32	8,700	7,310	10,300	14,700
PFC-3-1-10		2,600	0.33	7,000	6,330	8,860	12,500
PFC-4-1-12		4,100	0.41		6,510	9,160	13,300
PFC-5-1-14		3,200	0.49	7,400	6,600	9,300	13,300
PFC-9-1-18		>1,000d	0.56		>5,500	>7,500	>9,500
trifluoromethyl sulphur pentafluoride		800	0.57		13,200	17,700	21,200
Fluorinated ethers							
HFE-125		136	0.44		13,800	14,900	8,490
HFE-134		26	0.45		12,200	6,320	1,960
HFE-143a		4.3	0.27		2,630	756	230
HCFE-235da2		2.6	0.38		1,230	350	106
HFE-245cb2		5.1	0.32		2,440	708	215
HFE-245fa2		4.9	0.31		2,280	659	200
HFE-254cb2		2.6	0.28		1,260	359	109
HFE-347mcc3		5.2	0.34		1,980	575	175
HFE-347pcf2		7.1	0.25		1,900	580	175
HFE-356pcc3		0.33	0.93		386	110	33
HFE-449sl (HFE-7100)		3.8	0.31		1,040	297	90
HFE-569sf2 (HFE-7200)		0.77	0.3		207	59	18
HFE-43-10pccc124 (H-Galden 1040x)		6.3	1.37		6,320	1,870	569
HFE-236ca12 (HG-10)		12.1	0.66		8,000	2,800	860
HFE-338pcc13 (HG-01)		6.2	0.87		5,100	1,500	460
Perfluoropolyethers							
PFPMIE		800	0.65		7,620	10,300	12,400
Hydrocarbons and other compounds – Direct Effects							
Dimethylether		0.015	0.02		1	1	<<1
Methylene chloride		0.38	0.03		31	8.7	2.7
Methyl chloride		1.0	0.01		45	13	4

Table E.2 – Local Road Carbon Footprint Analysis Results

Process	CO_2e	NO_x [kg]	PM_{10} [kg]	SO_2 [kg]
Initial Construction				
HMA (Control)	12505	131	111	1788
HMA with RAP	12172	128	105	1787
HMA with RAS	11690	126	110	1766
Porous Asphalt	17163	164	155	1804
Pervious Concrete	15915	187	133	92
Warm Mix Asphalt	8768	75	111	1198
Maintenance and Rehabilitation				
Mill and HMA Overlay (Control)	9071	89	49	2427
Mill and HMA Overlay with RAP	8618	85	41	2427
Cold In-Place Recycling	4941	43	19	893
CIREAM	5203	45	19	895
Full Depth Reclamation	2336	23	13	618
Microsurfacing	921	10	6	284

Table E.3 – Laneway Carbon Footprint Analysis Results

Process	CO_2e	NO_x [kg]	PM_{10} [kg]	SO_2 [kg]
Initial Construction				
HMA (Control)	8091	85	72	1157
HMA with RAP	7876	83	68	1157
HMA with RAS	7564	82	71	1143
Porous Asphalt	11106	106	101	1167
Pervious Concrete	10298	121	86	59
Warm Mix Asphalt	5674	48	72	775
Maintenance and Rehabilitation				
Mill and HMA Overlay (Control)	5870	58	32	1571
Mill and HMA Overlay with RAP	5576	55	27	1570
Cold In-Place Recycling	3197	28	12	578
CIREAM	3367	29	12	579
Full Depth Reclamation	1511	15	8	400
Microsurfacing	596	7	4	184

Table E.4 – Minor Collector Carbon Footprint Analysis Results

Process	CO_2e	NO_x [kg]	PM_{10} [kg]	SO_2 [kg]
Initial Construction				
HMA (Control)	21569	225	194	3026
HMA with RAP	21004	220	185	3025
HMA with RAS	20191	217	193	2989
Porous Asphalt	29305	281	267	3046
Pervious Concrete	27122	319	228	155
Warm Mix Asphalt	15124	128	194	2027
Maintenance and Rehabilitation				
Mill and HMA Overlay (Control)	15349	150	83	4107
Mill and HMA Overlay with RAP	14579	144	69	4106
Cold In-Place Recycling	7433	66	30	1434
CIREAM	7773	68	30	1436
Full Depth Reclamation	3785	38	20	1004
Microsurfacing	1191	13	8	368

Table E.5 – Major Collector Carbon Footprint Analysis Results

Process	CO_2e	NO_x [kg]	PM_{10} [kg]	SO_2 [kg]
Initial Construction				
HMA (Control)	25491	266	229	3576
HMA with RAP	24823	260	218	3575
HMA with RAS	23862	256	228	3533
Porous Asphalt	34633	332	315	3599
Pervious Concrete	32053	377	269	183
Warm Mix Asphalt	17874	151	229	2396
Maintenance and Rehabilitation				
Mill and HMA Overlay (Control)	18140	178	98	4854
Mill and HMA Overlay with RAP	17229	170	82	4852
Cold In-Place Recycling	8784	78	35	1695
CIREAM	9186	80	36	1697
Full Depth Reclamation	4473	44	24	1187
Microsurfacing	1408	16	9	434

Table E.6 – Industrial Road Carbon Footprint Analysis Results

Process	CO_2e	NO_x [kg]	PM_{10} [kg]	SO_2 [kg]
Initial Construction				
HMA (Control)	25491	266	229	3576
HMA with RAP	24823	260	218	3575
HMA with RAS	23862	256	228	3533
Porous Asphalt	34633	332	315	3599
Pervious Concrete	32053	377	269	183
Warm Mix Asphalt	17874	151	229	2396
Maintenance and Rehabilitation				
Mill and HMA Overlay (Control)	18140	178	98	4854
Mill and HMA Overlay with RAP	17229	170	82	4852
Cold In-Place Recycling	8784	78	35	1695
CIREAM	9186	80	36	1697
Full Depth Reclamation	4473	44	24	1187
Microsurfacing	1408	16	9	434

Appendix E
Economical Analysis Results

Table F.1 – Industrial Economical Analysis Results

Total				
Technology	**Initial Construction NPV**	**Maintenance NPV**	**Initial Construction AC**	**Maintenance AC**
HMA (Control)	$ 516,129.00	$ -	$ 34,303.00	$ -
HMA with RAP	$ 481,053.00	$ -	$ 31,972.00	$ -
HMA with RAS	$ 512,610.00	$ -	$ 34,069.00	$ -
Porous Asphalt	$ 785,264.00	$ -	$ 52,190.00	$ -
Pervious Concrete	$ 1,492,542.00	$ -	$ 99,197.00	$ -
Warm Mix Asphalt	$ 540,433.00	$ -	$ 35,918.00	$ -
Technology	**Initial Construction NPV**	**Maintenance NPV**	**Initial Construction AC**	**Maintenance AC**
Mill and Overlay (Control)	$ -	$ 464,200.00	$ -	$ 30,851.00
Mill and Overlay with RAP	$ -	$ 430,399.00	$ -	$ 28,605.00
Cold In-Place Recycling	$ -	$ 217,760.00	$ -	$ 14,473.00
CIREAM	$ -	$ 276,325.00	$ -	$ 18,365.00
Full Depth Reclamation	$ -	$ 106,001.00	$ -	$ 7,045.00
Microsurfacing	$ -	$ 43,808.00	$ -	$ 2,912.00

Annual				
Technology	**Initial Construction NPV**	**Maintenance NPV**	**Initial Construction AC**	**Maintenance AC**
HMA (Control)	$ 34,408.60	$ -	$ 2,286.87	$ -
HMA with RAP	$ 32,070.20	$ -	$ 2,131.47	$ -
HMA with RAS	$ 34,174.00	$ -	$ 2,271.27	$ -
Porous Asphalt	$ 52,350.93	$ -	$ 3,479.33	$ -
Pervious Concrete	$ 74,627.10	$ -	$ 4,959.85	$ -
Warm Mix Asphalt	$ 36,028.87	$ -	$ 2,394.53	$ -
Technology	**Initial Construction NPV**	**Maintenance NPV**	**Initial Construction AC**	**Maintenance AC**
Mill and Overlay (Control)	$ -	$ 42,200.00	$ -	$ 2,804.64
Mill and Overlay with RAP	$ -	$ 39,127.18	$ -	$ 2,600.45
Cold In-Place Recycling	$ -	$ 19,796.36	$ -	$ 1,315.73
CIREAM	$ -	$ 25,120.45	$ -	$ 1,669.55
Full Depth Reclamation	$ -	$ 7,066.73	$ -	$ 469.67
Microsurfacing	$ -	$ 5,476.00	$ -	$ 364.00

Table F.2 – Laneway Economical Analysis Results

Total				
Technology	**Initial Construction NPV**	**Maintenance NPV**	**Initial Construction AC**	**Maintenance AC**
HMA (Control)	$ 166,318.00	$ -	$ 11,054.00	$ -
HMA with RAP	$ 155,012.00	$ -	$ 10,302.00	$ -
HMA with RAS	$ 165,180.00	$ -	$ 10,978.00	$ -
Porous Asphalt	$ 252,264.00	$ -	$ 16,766.00	$ -
Pervious Concrete	$ 481,568.00	$ -	$ 32,005.00	$ -
Warm Mix Asphalt	$ 174,182.00	$ -	$ 11,576.00	$ -
Technology	**Initial Construction NPV**	**Maintenance NPV**	**Initial Construction AC**	**Maintenance AC**
Mill and Overlay (Control)	$ -	$ 168,625.00	$ -	$ 11,207.00
Mill and Overlay with RAP	$ -	$ 157,859.00	$ -	$ 10,492.00
Cold In-Place Recycling	$ -	$ 84,138.00	$ -	$ 5,592.00
CIREAM	$ -	$ 108,916.00	$ -	$ 7,239.00
Full Depth Reclamation	$ -	$ 36,856.00	$ -	$ 2,450.00
Microsurfacing	$ -	$ 18,534.00	$ -	$ 1,232.00

Annual				
Technology	**Initial Construction NPV**	**Maintenance NPV**	**Initial Construction AC**	**Maintenance AC**
HMA (Control)	$ 11,087.87	$ -	$ 736.93	$ -
HMA with RAP	$ 10,334.13	$ -	$ 686.80	$ -
HMA with RAS	$ 11,012.00	$ -	$ 731.87	$ -
Porous Asphalt	$ 16,817.60	$ -	$ 1,117.73	$ -
Pervious Concrete	$ 24,078.40	$ -	$ 1,600.25	$ -
Warm Mix Asphalt	$ 11,612.13	$ -	$ 771.73	$ -
Technology	**Initial Construction NPV**	**Maintenance NPV**	**Initial Construction AC**	**Maintenance AC**
Mill and Overlay (Control)	$ -	$ 15,329.55	$ -	$ 1,018.82
Mill and Overlay with RAP	$ -	$ 14,350.82	$ -	$ 953.82
Cold In-Place Recycling	$ -	$ 7,648.91	$ -	$ 508.36
CIREAM	$ -	$ 9,901.45	$ -	$ 658.09
Full Depth Reclamation	$ -	$ 2,457.07	$ -	$ 163.33
Microsurfacing	$ -	$ 2,316.75	$ -	$ 154.00

Table F.3 – Local Economical Analysis Results

Total				
Technology	**Initial Construction NPV**	**Maintenance NPV**	**Initial Construction AC**	**Maintenance AC**
HMA (Control)	$ 257,037.00	$ -	$ 17,083.00	$ -
HMA with RAP	$ 239,564.00	$ -	$ 15,922.00	$ -
HMA with RAS	$ 255,278.00	$ -	$ 16,966.00	$ -
Porous Asphalt	$ 389,862.00	$ -	$ 25,911.00	$ -
Pervious Concrete	$ 744,233.00	$ -	$ 49,463.00	$ -
Warm Mix Asphalt	$ 269,191.00	$ -	$ 17,891.00	$ -
Technology	**Initial Construction NPV**	**Maintenance NPV**	**Initial Construction AC**	**Maintenance AC**
Mill and Overlay (Control)	$ -	$ 260,603.00	$ -	$ 17,320.00
Mill and Overlay with RAP	$ -	$ 243,963.00	$ -	$ 16,214.00
Cold In-Place Recycling	$ -	$ 130,033.00	$ -	$ 8,642.00
CIREAM	$ -	$ 168,325.00	$ -	$ 11,187.00
Full Depth Reclamation	$ -	$ 56,959.00	$ -	$ 3,786.00
Microsurfacing	$ -	$ 28,643.00	$ -	$ 1,904.00

Annual				
Technology	**Initial Construction NPV**	**Maintenance NPV**	**Initial Construction AC**	**Maintenance AC**
HMA (Control)	$ 17,135.80	$ -	$ 1,138.87	$ -
HMA with RAP	$ 15,970.93	$ -	$ 1,061.47	$ -
HMA with RAS	$ 17,018.53	$ -	$ 1,131.07	$ -
Porous Asphalt	$ 25,990.80	$ -	$ 1,727.40	$ -
Pervious Concrete	$ 37,211.65	$ -	$ 2,473.15	$ -
Warm Mix Asphalt	$ 17,946.07	$ -	$ 1,192.73	$ -
Technology	**Initial Construction NPV**	**Maintenance NPV**	**Initial Construction AC**	**Maintenance AC**
Mill and Overlay (Control)	$ -	$ 23,691.18	$ -	$ 1,574.55
Mill and Overlay with RAP	$ -	$ 22,178.45	$ -	$ 1,474.00
Cold In-Place Recycling	$ -	$ 11,821.18	$ -	$ 785.64
CIREAM	$ -	$ 15,302.27	$ -	$ 1,017.00
Full Depth Reclamation	$ -	$ 3,797.27	$ -	$ 252.40
Microsurfacing	$ -	$ 3,580.38	$ -	$ 238.00

Table F.4 –Major Collector Economical Analysis Results

Total				
Technology	**Initial Construction NPV**	**Maintenance NPV**	**Initial Construction AC**	**Maintenance AC**
HMA (Control)	$ 516,129.00	$ -	$ 34,303.00	$ -
HMA with RAP	$ 481,053.00	$ -	$ 31,972.00	$ -
HMA with RAS	$ 512,610.00	$ -	$ 34,069.00	$ -
Porous Asphalt	$ 785,264.00	$ -	$ 52,190.00	$ -
Pervious Concrete	$ 1,492,542.00	$ -	$ 99,197.00	$ -
Warm Mix Asphalt	$ 540,433.00	$ -	$ 35,918.00	$ -
Technology	**Initial Construction NPV**	**Maintenance NPV**	**Initial Construction AC**	**Maintenance AC**
Mill and Overlay (Control)	$ -	$ 464,200.00	$ -	$ 30,851.00
Mill and Overlay with RAP	$ -	$ 430,399.00	$ -	$ 28,605.00
Cold In-Place Recycling	$ -	$ 217,760.00	$ -	$ 14,473.00
CIREAM	$ -	$ 276,325.00	$ -	$ 18,365.00
Full Depth Reclamation	$ -	$ 106,001.00	$ -	$ 7,045.00
Microsurfacing	$ -	$ 43,808.00	$ -	$ 2,912.00

Annual				
Technology	**Initial Construction NPV**	**Maintenance NPV**	**Initial Construction AC**	**Maintenance AC**
HMA (Control)	$ 34,408.60	$ -	$ 2,286.87	$ -
HMA with RAP	$ 32,070.20	$ -	$ 2,131.47	$ -
HMA with RAS	$ 34,174.00	$ -	$ 2,271.27	$ -
Porous Asphalt	$ 52,350.93	$ -	$ 3,479.33	$ -
Pervious Concrete	$ 74,627.10	$ -	$ 4,959.85	$ -
Warm Mix Asphalt	$ 36,028.87	$ -	$ 2,394.53	$ -
Technology	**Initial Construction NPV**	**Maintenance NPV**	**Initial Construction AC**	**Maintenance AC**
Mill and Overlay (Control)	$ -	$ 42,200.00	$ -	$ 2,804.64
Mill and Overlay with RAP	$ -	$ 39,127.18	$ -	$ 2,600.45
Cold In-Place Recycling	$ -	$ 19,796.36	$ -	$ 1,315.73
CIREAM	$ -	$ 25,120.45	$ -	$ 1,669.55
Full Depth Reclamation	$ -	$ 7,066.73	$ -	$ 469.67
Microsurfacing	$ -	$ 5,476.00	$ -	$ 364.00

Table F.5 – Minor Collector Economical Analysis Results

Total				
Technology	Initial Construction NPV	Maintenance NPV	Initial Construction AC	Maintenance AC
HMA (Control)	$ 436,723.00	$ -	$ 29,025.00	$ -
HMA with RAP	$ 407,043.00	$ -	$ 27,053.00	$ -
HMA with RAS	$ 433,746.00	$ -	$ 28,827.00	$ -
Porous Asphalt	$ 664,455.00	$ -	$ 44,161.00	$ -
Pervious Concrete	$ 1,262,920.00	$ -	$ 83,936.00	$ -
Warm Mix Asphalt	$ 457,288.00	$ -	$ 30,392.00	$ -
Technology	Initial Construction NPV	Maintenance NPV	Initial Construction AC	Maintenance AC
Mill and Overlay (Control)	$ -	$ 392,785.00	$ -	$ 26,105.00
Mill and Overlay with RAP	$ -	$ 364,184.00	$ -	$ 24,204.00
Cold In-Place Recycling	$ -	$ 184,258.00	$ -	$ 12,246.00
CIREAM	$ -	$ 233,814.00	$ -	$ 15,540.00
Full Depth Reclamation	$ -	$ 89,693.00	$ -	$ 5,961.00
Microsurfacing	$ -	$ 37,068.00	$ -	$ 2,464.00

Annual				
Technology	Initial Construction NPV	Maintenance NPV	Initial Construction AC	Maintenance AC
HMA (Control)	$ 29,114.87	$ -	$ 1,935.00	$ -
HMA with RAP	$ 27,136.20	$ -	$ 1,803.53	$ -
HMA with RAS	$ 28,916.40	$ -	$ 1,921.80	$ -
Porous Asphalt	$ 44,297.00	$ -	$ 2,944.07	$ -
Pervious Concrete	$ 63,146.00	$ -	$ 4,196.80	$ -
Warm Mix Asphalt	$ 30,485.87	$ -	$ 2,026.13	$ -
Technology	Initial Construction NPV	Maintenance NPV	Initial Construction AC	Maintenance AC
Mill and Overlay (Control)	$ -	$ 35,707.73	$ -	$ 2,373.18
Mill and Overlay with RAP	$ -	$ 33,107.64	$ -	$ 2,200.36
Cold In-Place Recycling	$ -	$ 16,750.73	$ -	$ 1,113.27
CIREAM	$ -	$ 21,255.82	$ -	$ 1,412.73
Full Depth Reclamation	$ -	$ 5,979.53	$ -	$ 397.40
Microsurfacing	$ -	$ 4,633.50	$ -	$ 308.00

Appendix F
GreenPave Analysis Results

Table G.1 – Hot Mix Asphalt GreenPave Results

Category	Sub-Category	Max Points	Awarded Points
Pavement Technologies	Long Life Pavement	3	0
	Permeable Pavement	2	0
	Noise Mitigation	2	1
	Cool Pavement	2	0
Materials & Resources	Recycled Content	5	2.4
	Reuse of Pavement	2	0
	Local Materials	2	2
	Construction Quality	2	1
Energy & Atmosphere	Reduce Energy Consumption	3	0.8
	GHG Emissions Reduction	3	0.8
	Pavement Smoothness	1	1
	Pollution Reduction	1	0
Innovations & Design Processes	Innovation in Design	2	0
	Exemplary Process	2	0
	Total:	32	**9**

Table G.2 – Hot Mix Asphalt with Reclaimed Asphalt Pavement GreenPave Results

Category	Sub-Category	Max Points	Awarded Points
Pavement Technologies	Long Life Pavement	3	0
	Permeable Pavement	2	0
	Noise Mitigation	2	1
	Cool Pavement	2	0
Materials & Resources	Recycled Content	5	2.7
	Reuse of Pavement	2	0
	Local Materials	2	2
	Construction Quality	2	1
Energy & Atmosphere	Reduce Energy Consumption	3	1.1
	GHG Emissions Reduction	3	1.1
	Pavement Smoothness	1	1
	Pollution Reduction	1	0
Innovations & Design Processes	Innovation in Design	2	0
	Exemplary Process	2	0
	Total:	32	**9.9**

Table G.3 – Hot Mix Asphalt with Recycled Asphalt Shingles GreenPave Results

Category	Sub-Category	Max Points	Awarded Points
Pavement Technologies	Long Life Pavement	3	0
	Permeable Pavement	2	0
	Noise Mitigation	2	1
	Cool Pavement	2	0
Materials & Resources	Recycled Content	5	3.4
	Reuse of Pavement	2	0
	Local Materials	2	2
	Construction Quality	2	1
Energy & Atmosphere	Reduce Energy Consumption	3	1
	GHG Emissions Reduction	3	0.8
	Pavement Smoothness	1	1
	Pollution Reduction	1	0
Innovations & Design Processes	Innovation in Design	2	0
	Exemplary Process	2	0
	Total:	32	**10.2**

Table G.4 – Porous Asphalt GreenPave Results

Category	Sub-Category	Max Points	Awarded Points
Pavement Technologies	Long Life Pavement	3	0
	Permeable Pavement	2	2
	Noise Mitigation	2	0
	Cool Pavement	2	1
Materials & Resources	Recycled Content	5	0
	Reuse of Pavement	2	0
	Local Materials	2	2
	Construction Quality	2	1
Energy & Atmosphere	Reduce Energy Consumption	3	0
	GHG Emissions Reduction	3	0
	Pavement Smoothness	1	1
	Pollution Reduction	1	0
Innovations & Design Processes	Innovation in Design	2	0
	Exemplary Process	2	0
	Total:	32	**7**

Table G.5 – Pervious Concrete GreenPave Results

Category	Sub-Category	Max Points	Awarded Points
Pavement Technologies	Long Life Pavement	3	3
	Permeable Pavement	2	2
	Noise Mitigation	2	0
	Cool Pavement	2	2
Materials & Resources	Recycled Content	5	0
	Reuse of Pavement	2	0
	Local Materials	2	2
	Construction Quality	2	1
Energy & Atmosphere	Reduce Energy Consumption	3	0
	GHG Emissions Reduction	3	0
	Pavement Smoothness	1	1
	Pollution Reduction	1	0
Innovations & Design Processes	Innovation in Design	2	0
	Exemplary Process	2	0
	Total:	32	**11**

Table G.6 – Warm Mix Asphalt GreenPave Results

Category	Sub-Category	Max Points	Awarded Points
Pavement Technologies	Long Life Pavement	3	0
	Permeable Pavement	2	0
	Noise Mitigation	2	0
	Cool Pavement	2	2
Materials & Resources	Recycled Content	5	2.4
	Reuse of Pavement	2	0
	Local Materials	2	2
	Construction Quality	2	1
Energy & Atmosphere	Reduce Energy Consumption	3	1
	GHG Emissions Reduction	3	1
	Pavement Smoothness	1	1
	Pollution Reduction	1	0
Innovations & Design Processes	Innovation in Design	2	0
	Exemplary Process	2	0
	Total:	32	**10.4**

Table G.7 – Mill and Overlay GreenPave Results

Category	Sub-Category	Max Points	Awarded Points
Pavement Technologies	Long Life Pavement	3	0
	Permeable Pavement	2	0
	Noise Mitigation	2	1
	Cool Pavement	2	0
Materials & Resources	Recycled Content	5	0
	Reuse of Pavement	2	0
	Local Materials	2	2
	Construction Quality	2	1
Energy & Atmosphere	Reduce Energy Consumption	3	0
	GHG Emissions Reduction	3	0
	Pavement Smoothness	1	1
	Pollution Reduction	1	0
Innovations & Design Processes	Innovation in Design	2	0
	Exemplary Process	2	0
	Total:	32	**5**

Table G.8 – Mill and Overlay with Reclaimed Asphalt Pavement GreenPave Results

Category	Sub-Category	Max Points	Awarded Points
Pavement Technologies	Long Life Pavement	3	0
	Permeable Pavement	2	0
	Noise Mitigation	2	1
	Cool Pavement	2	0
Materials & Resources	Recycled Content	5	1
	Reuse of Pavement	2	0
	Local Materials	2	2
	Construction Quality	2	1
Energy & Atmosphere	Reduce Energy Consumption	3	1.7
	GHG Emissions Reduction	3	1.7
	Pavement Smoothness	1	1
	Pollution Reduction	1	0
Innovations & Design Processes	Innovation in Design	2	0
	Exemplary Process	2	0
	Total:	32	**9.4**

Table G.9 – Cold In-Place Recycling GreenPave Results

Category	Sub-Category	Max Points	Awarded Points
Pavement Technologies	Long Life Pavement	3	0
	Permeable Pavement	2	0
	Noise Mitigation	2	1
	Cool Pavement	2	0
Materials & Resources	Recycled Content	5	5
	Reuse of Pavement	2	0
	Local Materials	2	2
	Construction Quality	2	1
Energy & Atmosphere	Reduce Energy Consumption	3	3
	GHG Emissions Reduction	3	3
	Pavement Smoothness	1	1
	Pollution Reduction	1	0
Innovations & Design Processes	Innovation in Design	2	0
	Exemplary Process	2	0
	Total:	32	**16**

Table G.10 – Cold In-Place Recycling with Expanded Asphalt Mix GreenPave Results

Category	Sub-Category	Max Points	Awarded Points
Pavement Technologies	Long Life Pavement	3	0
	Permeable Pavement	2	0
	Noise Mitigation	2	1
	Cool Pavement	2	0
Materials & Resources	Recycled Content	5	5
	Reuse of Pavement	2	0
	Local Materials	2	2
	Construction Quality	2	1
Energy & Atmosphere	Reduce Energy Consumption	3	3
	GHG Emissions Reduction	3	3
	Pavement Smoothness	1	1
	Pollution Reduction	1	0
Innovations & Design Processes	Innovation in Design	2	0
	Exemplary Process	2	0
	Total:	32	**16**

Table G.11 – Full Depth Reclamation GreenPave Results

Category	Sub-Category	Max Points	Awarded Points
Pavement Technologies	Long Life Pavement	3	0
	Permeable Pavement	2	0
	Noise Mitigation	2	1
	Cool Pavement	2	0
Materials & Resources	Recycled Content	5	5
	Reuse of Pavement	2	0
	Local Materials	2	2
	Construction Quality	2	1
Energy & Atmosphere	Reduce Energy Consumption	3	3
	GHG Emissions Reduction	3	3
	Pavement Smoothness	1	1
	Pollution Reduction	1	0
Innovations & Design Processes	Innovation in Design	2	0
	Exemplary Process	2	0
	Total:	32	**16**

Table G.12 – Microsurfacing GreenPave Results

Category	Sub-Category	Max Points	Awarded Points
Pavement Technologies	Long Life Pavement	3	0
	Permeable Pavement	2	0
	Noise Mitigation	2	0
	Cool Pavement	2	0
Materials & Resources	Recycled Content	5	0
	Reuse of Pavement	2	1
	Local Materials	2	2
	Construction Quality	2	1
Energy & Atmosphere	Reduce Energy Consumption	3	0
	GHG Emissions Reduction	3	0
	Pavement Smoothness	1	1
	Pollution Reduction	1	0
Innovations & Design Processes	Innovation in Design	2	0
	Exemplary Process	2	0
	Total:	32	**5**

Table G.13 – Discount Factor Sensitivity Analysis Results

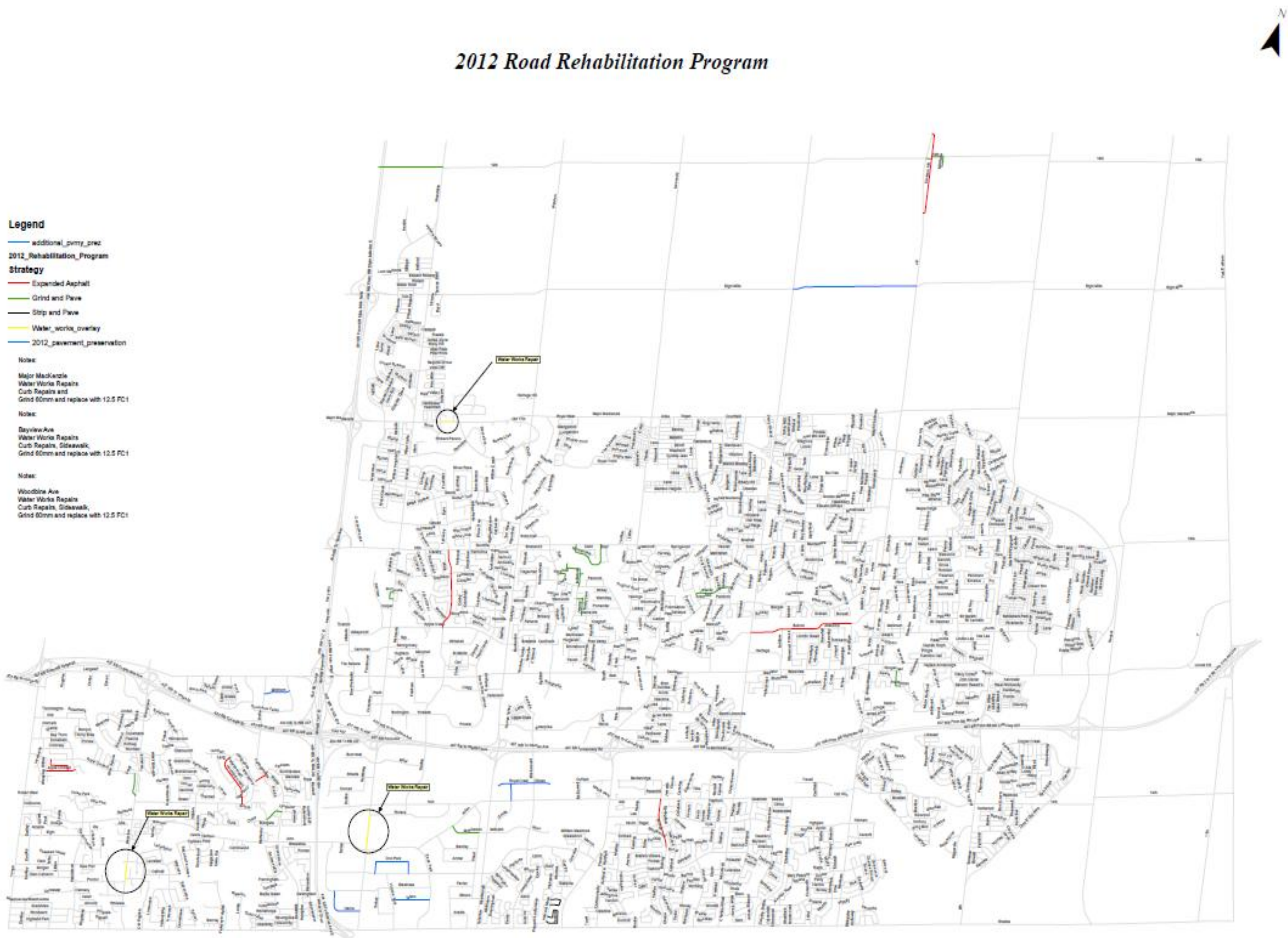
Technology	GreenPave Score	Certification Level	GDLCC (A=0)	GDLCC (A=0.1)	GDLCC (A=0.2)	GDLCC (A=0.3)	GDLCC (A=0.4)	GDLCC (A=0.5)
HMA	9	Not Certified	$257,037.00	$ 249,807.83	$ 242,578.67	$ 235,349.50	$ 228,120.34	$ 220,891.17
HMA with RAP	9.9	Not Certified	$239,564.00	$ 232,152.49	$ 224,740.98	$ 217,329.47	$ 209,917.96	$ 202,506.44
HMA with RAS	10.2	Bronze	$255,278.00	$ 247,141.01	$ 239,004.03	$ 230,867.04	$ 222,730.06	$ 214,593.07
Porous Asphalt	7	Not Certified	$321,756.00	$ 314,717.59	$ 307,679.18	$ 300,640.76	$ 293,602.35	$ 286,563.94
Pervious Concrete	11	Bronze	$744,233.00	$ 718,649.99	$ 693,066.98	$ 667,483.97	$ 641,900.96	$ 616,317.95
WMA	10.4	Bronze	$269,191.00	$ 260,442.29	$ 251,693.59	$ 242,944.88	$ 234,196.17	$ 225,447.46

Technology	GreenPave Score	Certification Level	GDLCC (A=0)	GDLCC (A=0.1)	GDLCC (A=0.2)	GDLCC (A=0.3)	GDLCC (A=0.4)	GDLCC (A=0.5)
Mill and Overlay	5	Not Certified	$260,603.00	$ 256,531.08	$ 252,459.16	$ 248,387.23	$ 244,315.31	$ 240,243.39
M&O with RAP	9.4	Not Certified	$243,963.00	$ 236,796.59	$ 229,630.17	$ 222,463.76	$ 215,297.35	$ 208,130.93
CIP	16	Silver	$130,033.00	$ 123,531.35	$ 117,029.70	$ 110,528.05	$ 104,026.40	$ 97,524.75
CIREAM	16	Silver	$168,325.00	$ 159,908.75	$ 151,492.50	$ 143,076.25	$ 134,660.00	$ 126,243.75
FDR	16	Silver	$ 56,959.00	$ 54,111.05	$ 51,263.10	$ 48,415.15	$ 45,567.20	$ 42,719.25
Microsurfacing	5	Not Certified	$ 28,643.00	$ 28,195.45	$ 27,747.91	$ 27,300.36	$ 26,852.81	$ 26,405.27

Appendix G

Current Road Network Condition and 2012 Road Rehabilitation Program

2012 Road Rehabilitation Program



2012 Road Rehabilitation Program